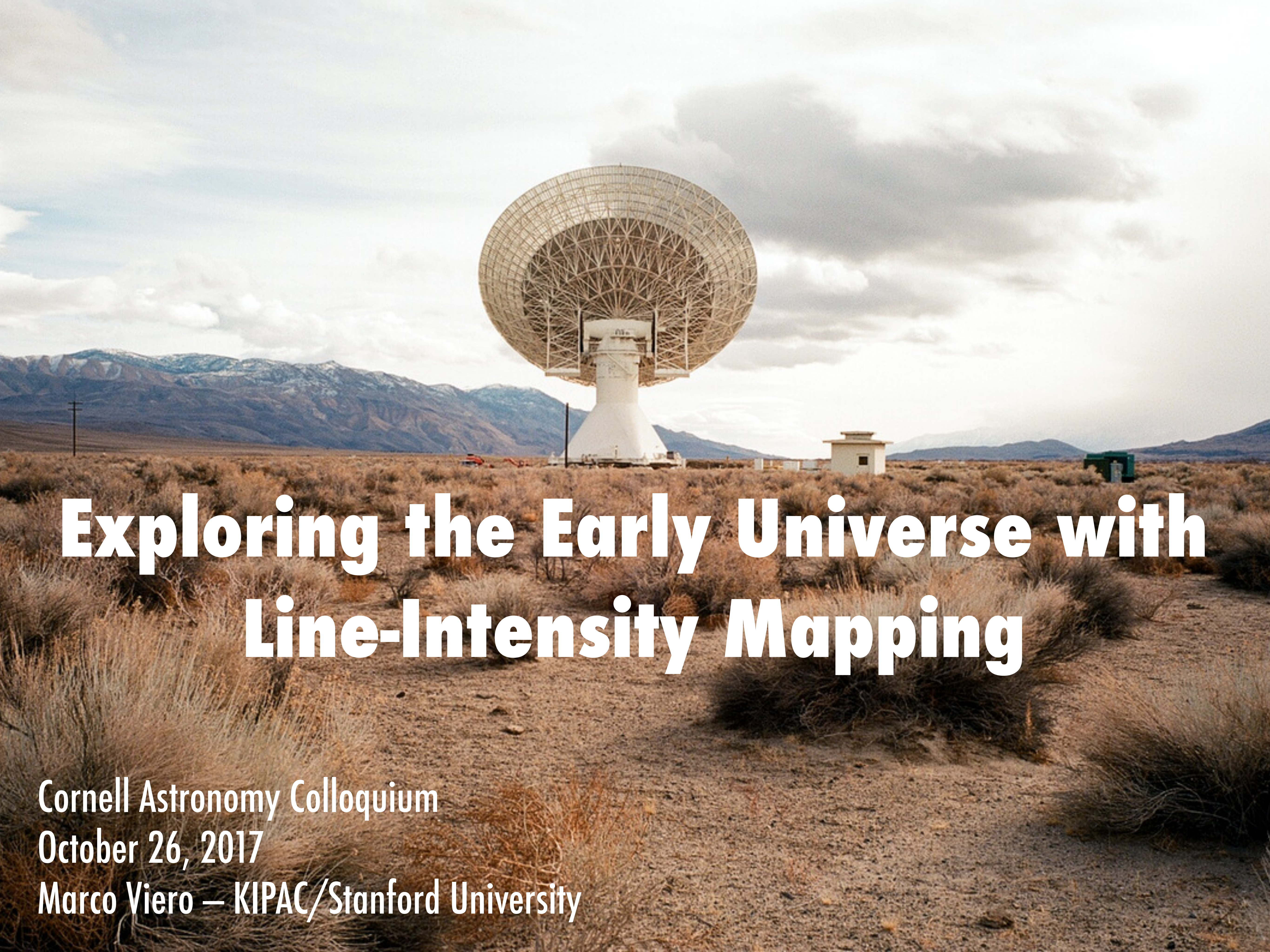


Exploring the Early Universe with Line-Intensity Mapping

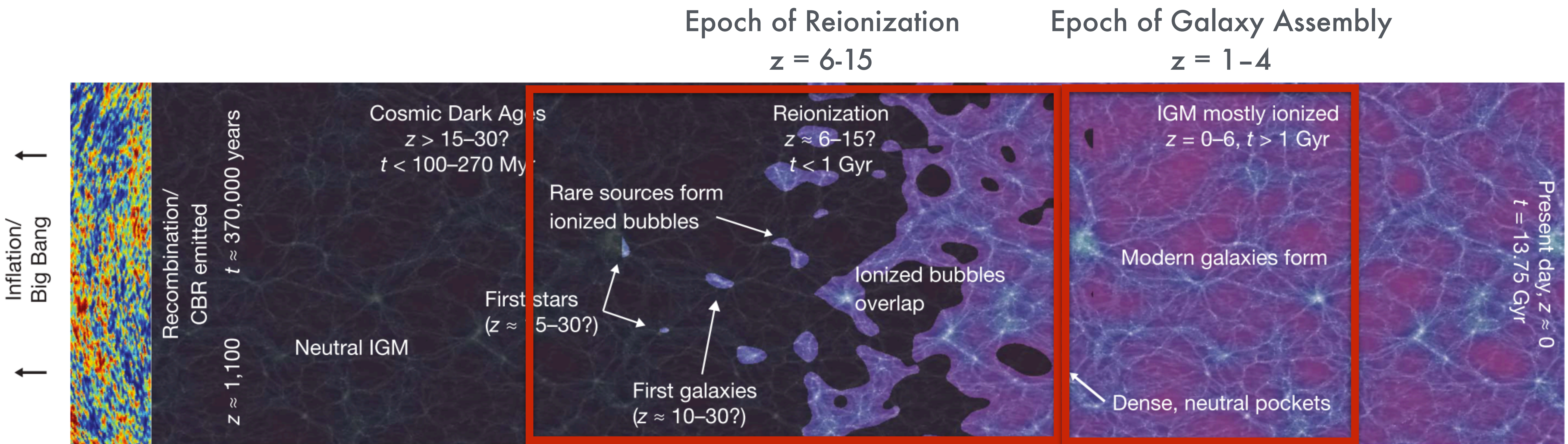
Cornell Astronomy Colloquium
October 26, 2017

Marco Viero – KIPAC/Stanford University

Outline

- The Early Universe — Motivation
  - ➡The Epoch of Reionization
  - ➡The Epoch of Galaxy Assembly
- Embracing Statistical Techniques
  - ➡Summary of Different Approaches
  - ➡The CIB — A Success Story
- Line-Intensity Mapping
  - ➡From IGM to Galaxies
  - ➡First Detections
  - ➡The Experimental Landscape

Early Universe

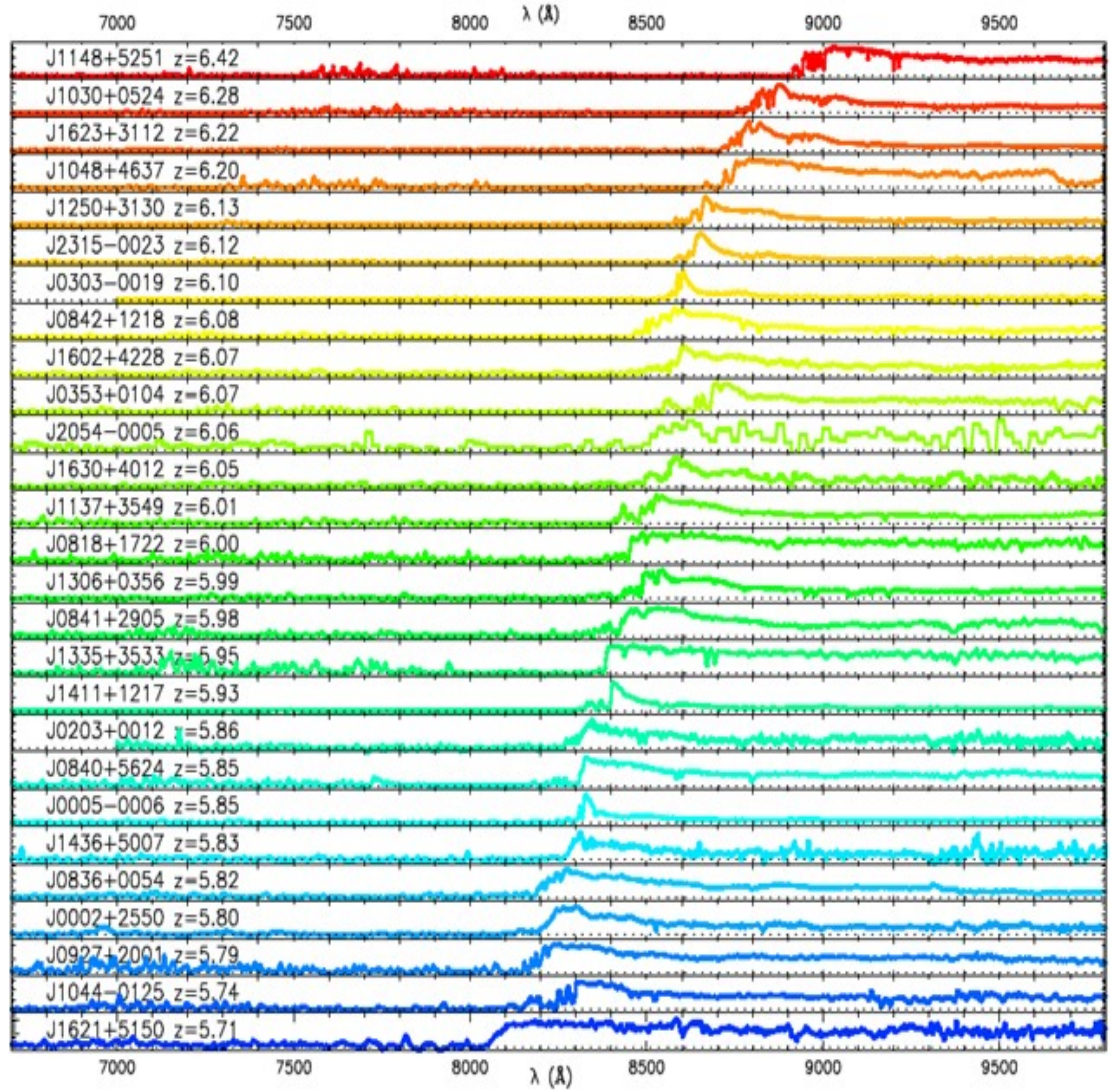


Robertson (2010)

- Epoch of Reionization:
  - ➡ When did the EoR begin/end?
  - ➡ Which galaxies are primarily responsible? SFG? AGN?
  - ➡ Is most of the work done by a few luminous or many faint galaxies?
- Epoch of Galaxy Assembly:
  - ➡ What sets the star-formation efficiency in early galaxy populations?
  - ➡ What is the role of gas supply in explaining the Universe's star-formation history?

EoR — Know: Reionization was Patchy

- Gunn-Peterson trough traces reionization via absorption of Lyman-alpha in quasar spectra.
- Reionization is patchy: depending on where you point, redshift of Gunn-Peterson trough varies.
- Reionization is fully completed by z ~ 5.

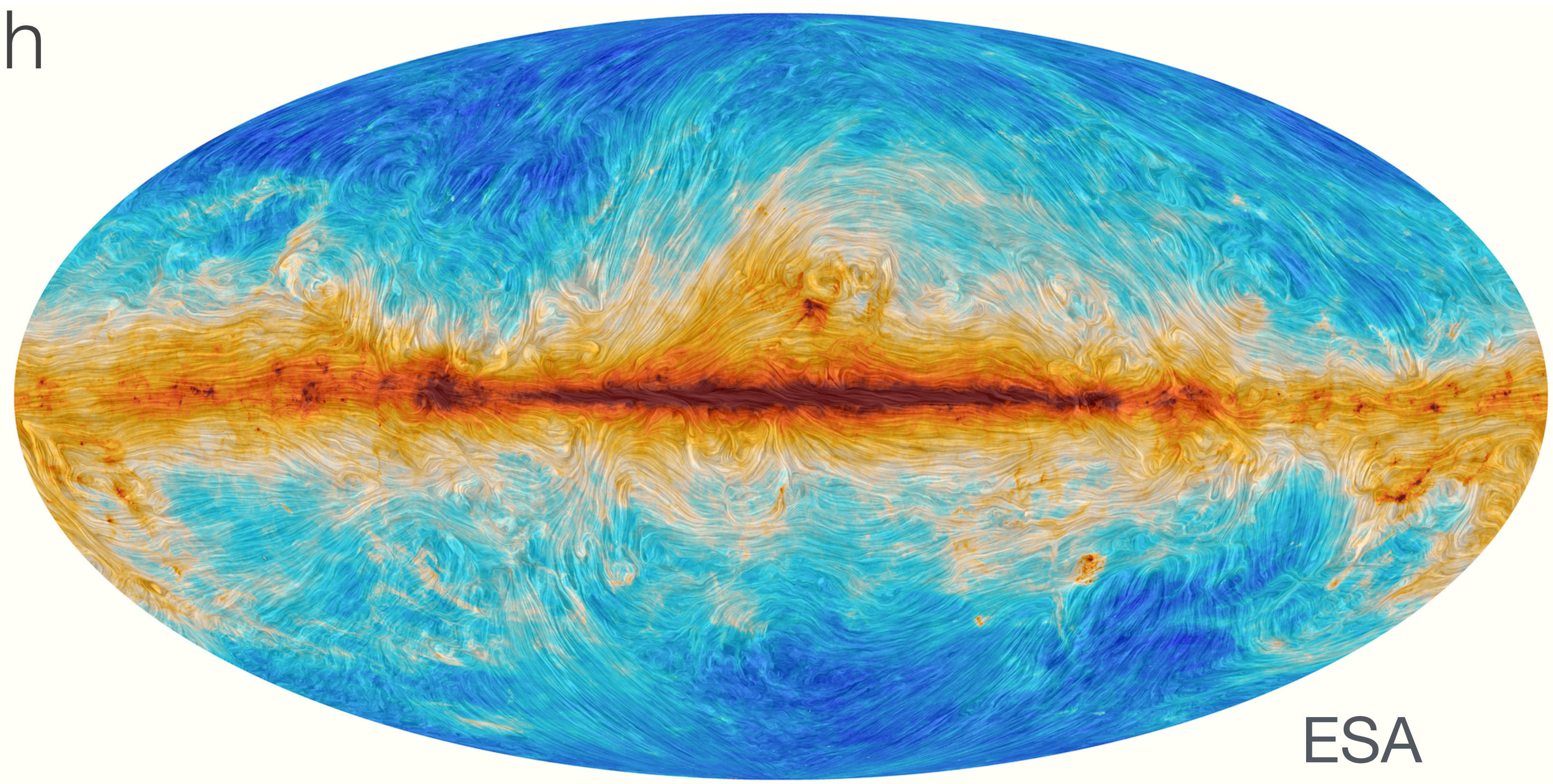


Fan et al. (2006) — arXiv:0512082
Becker et al. (2015) — arXiv:1407.4850

EoR — Know: Optical Depth to Reionization

- Planck E-mode polarization maps enable measurement of Thomson optical depth $\tau = 0.065$
  - ➡puts instantaneous reionization at $z = 8.8 \pm 1.5$
- Previously WMAP had $\tau = 0.089$
  - ➡instantaneous reionization at $z = 10.5$

Planck 353 GHz B-Field



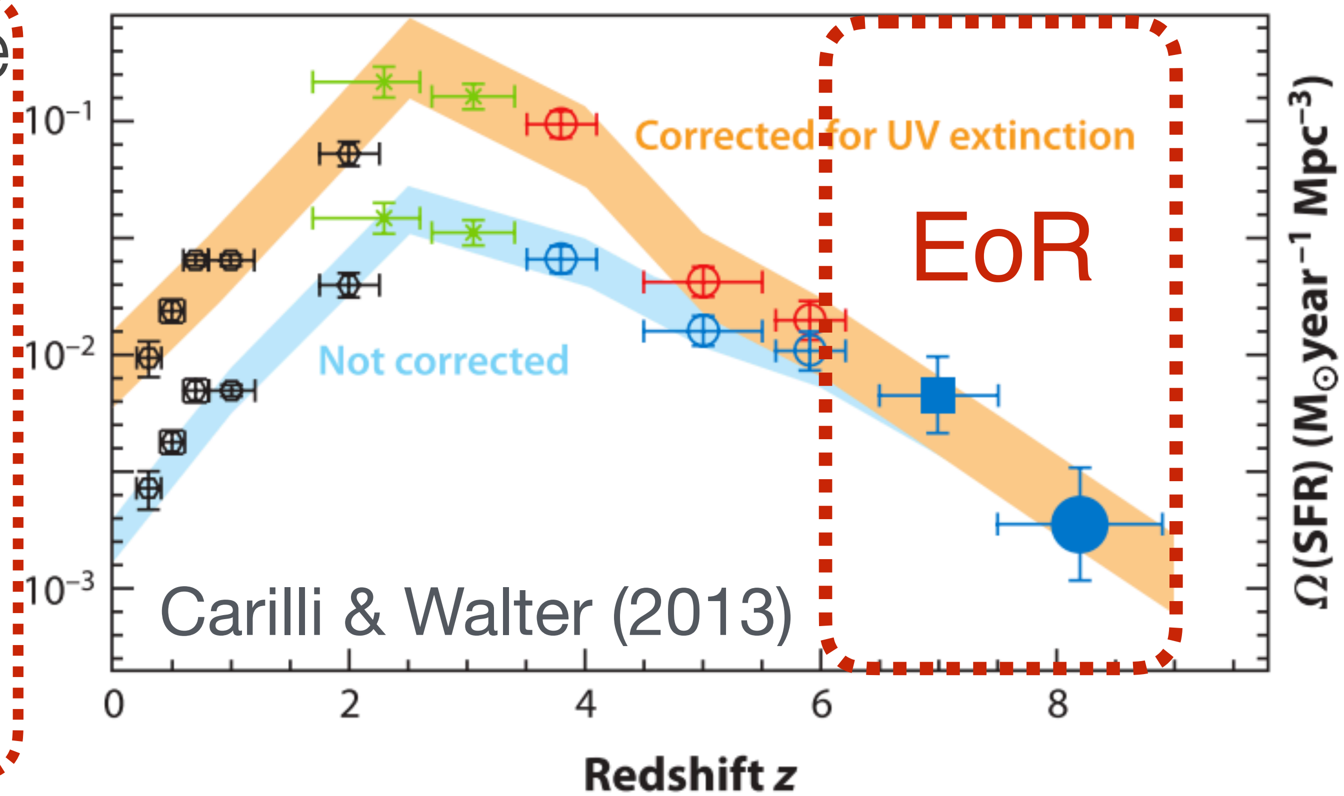
Planck Collaboration (2015) — arXiv:1502.01589

Reionization: A Balancing Act

Ionizations  **Recombinations**

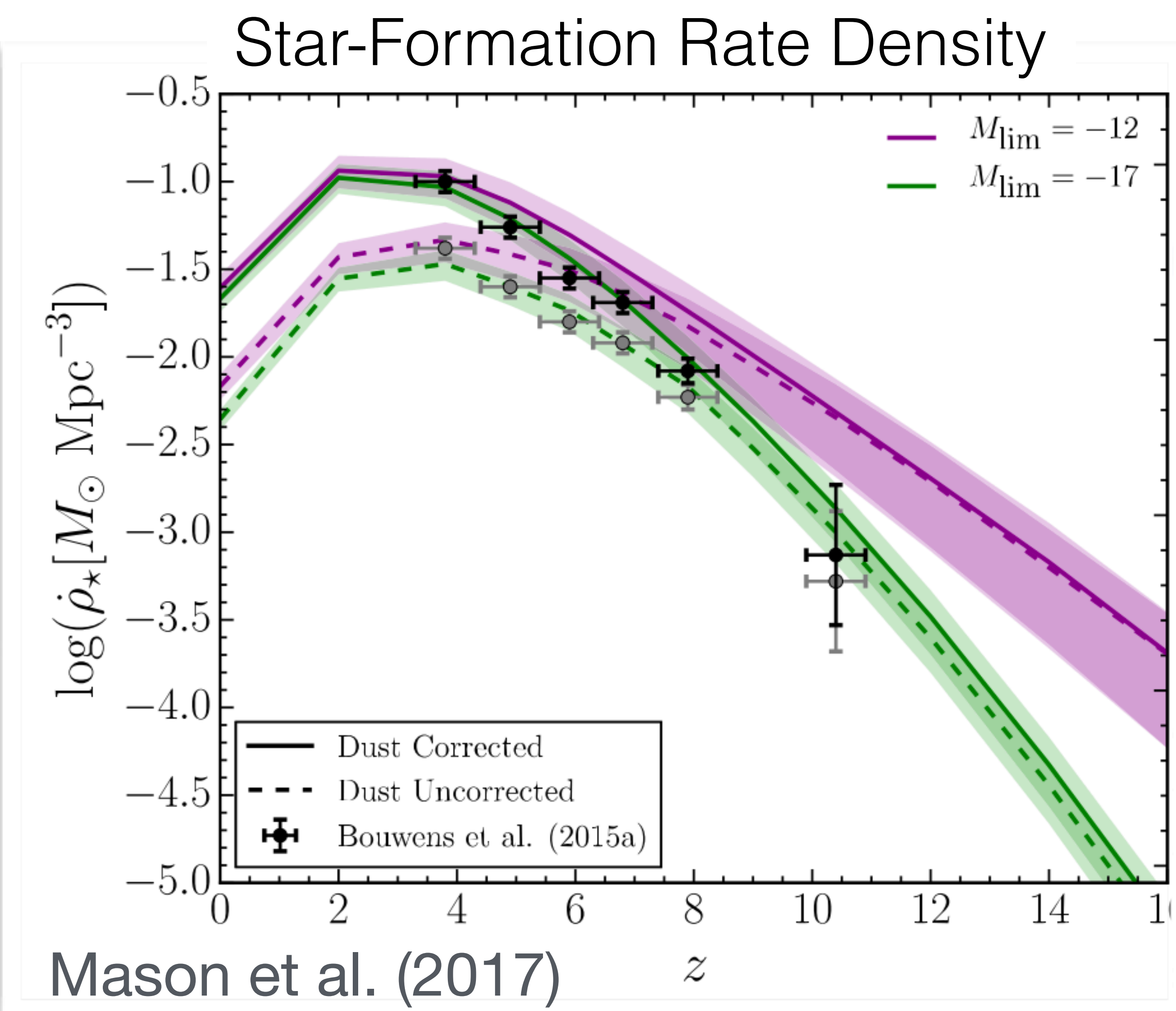
- f_{esc} : Escape fraction of ionizing photons.
- ζ_Q : Number of ionizing photons per UV luminosity.
- ρ_{SFR}: Comoving star-formation rate (UV luminosity) density.
  - high-z galaxies are identified as Lyman-break dropouts.
    - ✦Missing faint dusty sources?
  - ρ_{SFR} inferred via the UV luminosity function.

- T_{IGM}: IGM temperature.
- ρ_{HI} : Physical hydrogen density.
- C_{HII} : Clumping factor

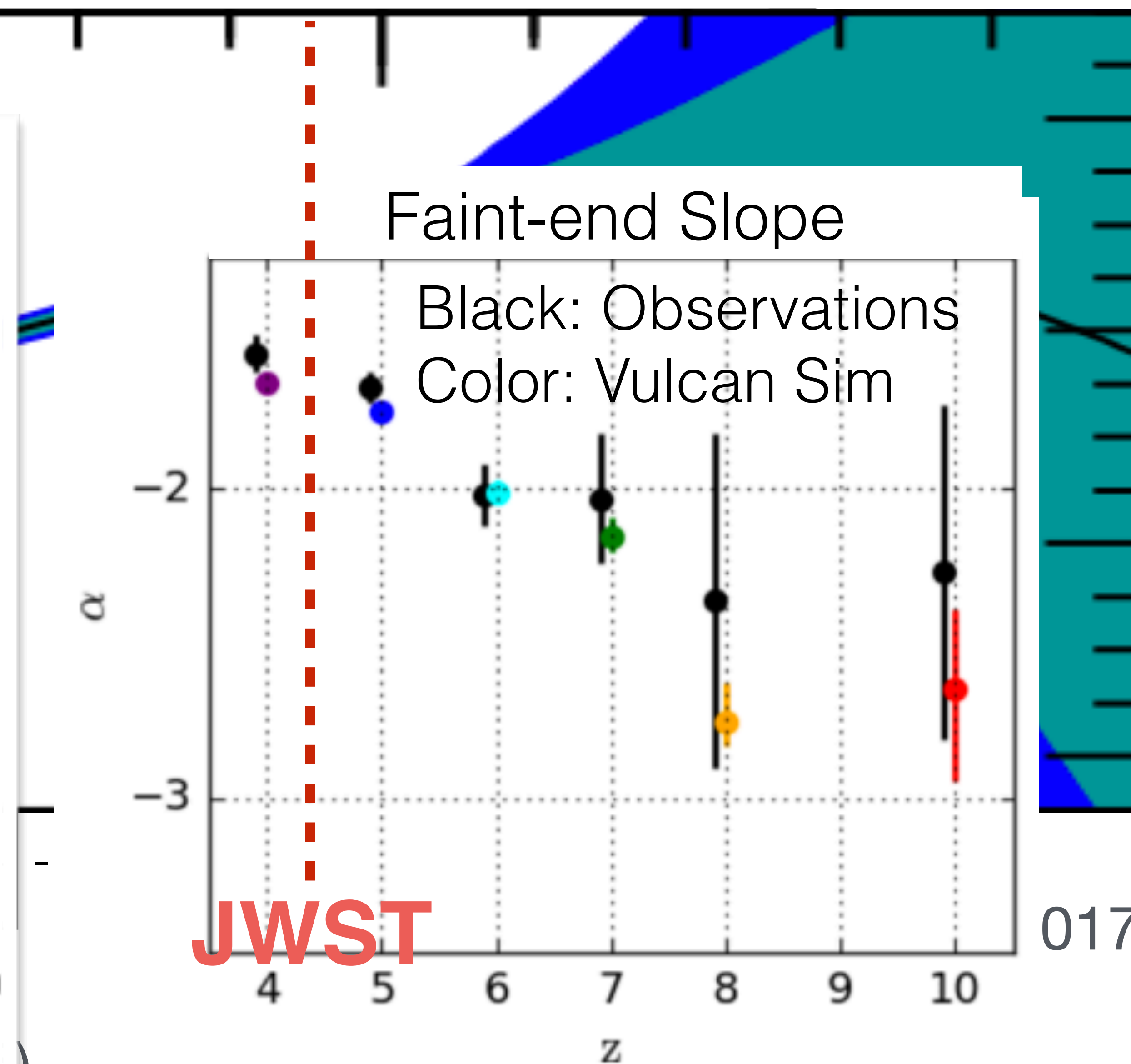


EoR — Don't Know: Faint-end of the Luminosity Function

- Slope determines which population dominates the power:
  - ➡ Does slope evolve with redshift? Where does it turn over?
- Sources fainter than -16 measured via magnification from cluster lensing. Subject to systematics (e.g., lensing model, shear, etc.)



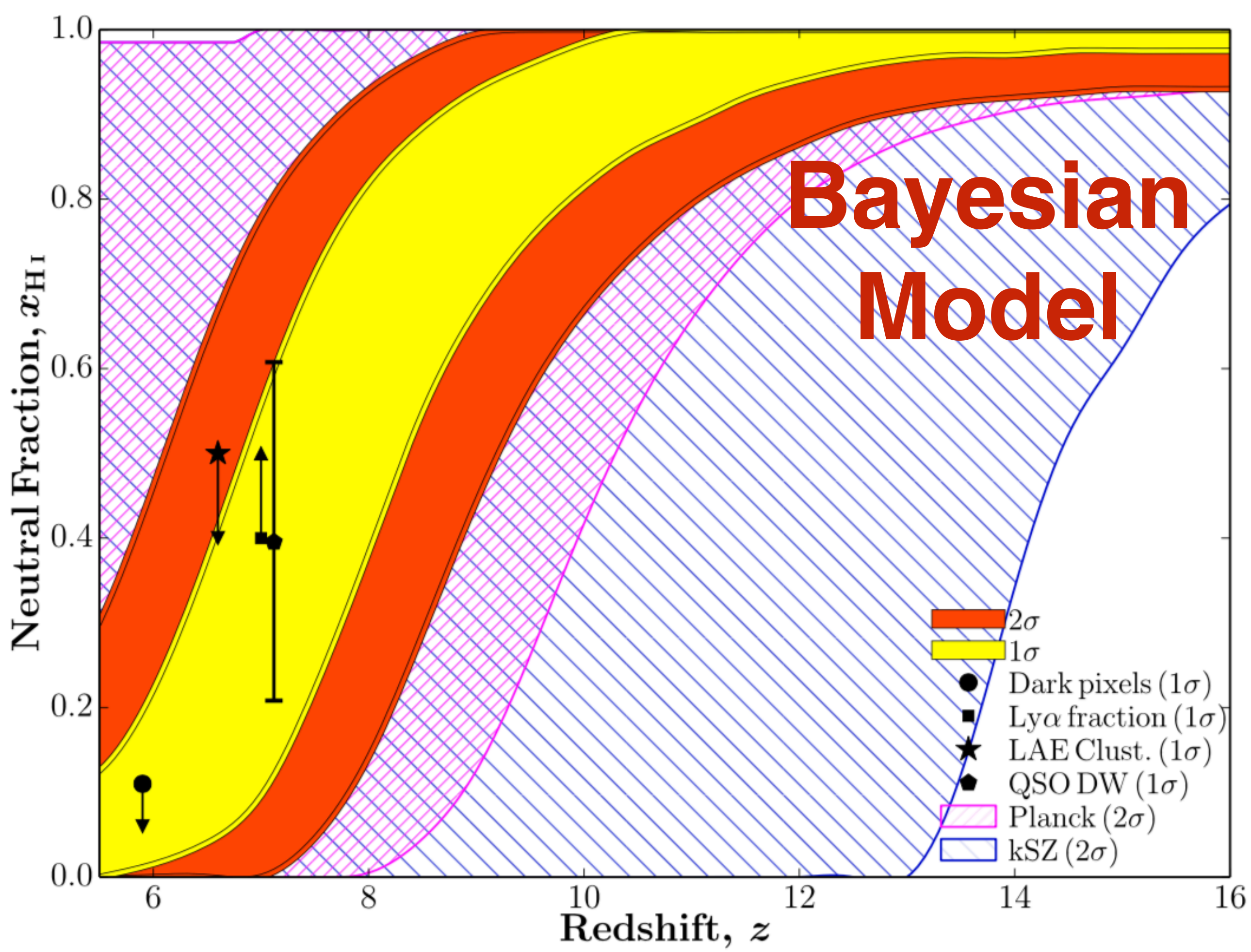
Mason et al. (2017)



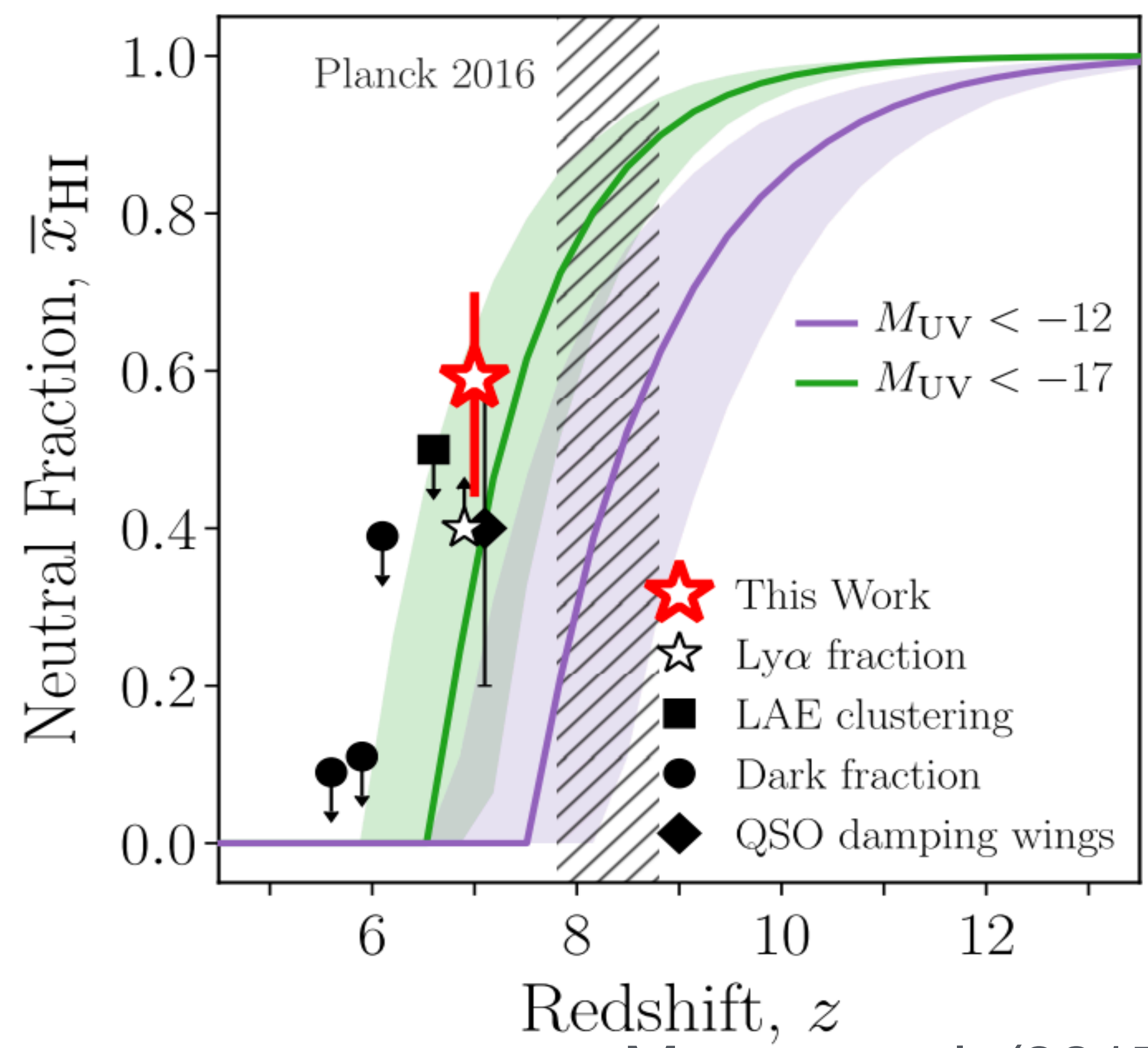
Anderson et al. (2017)

EoR — Don't Know: Evolution of Neutral Fraction

- Combining all existing observations leads to a wide range of possibilities.
- The existence of a significant faint contribution would push reionization to earlier times.



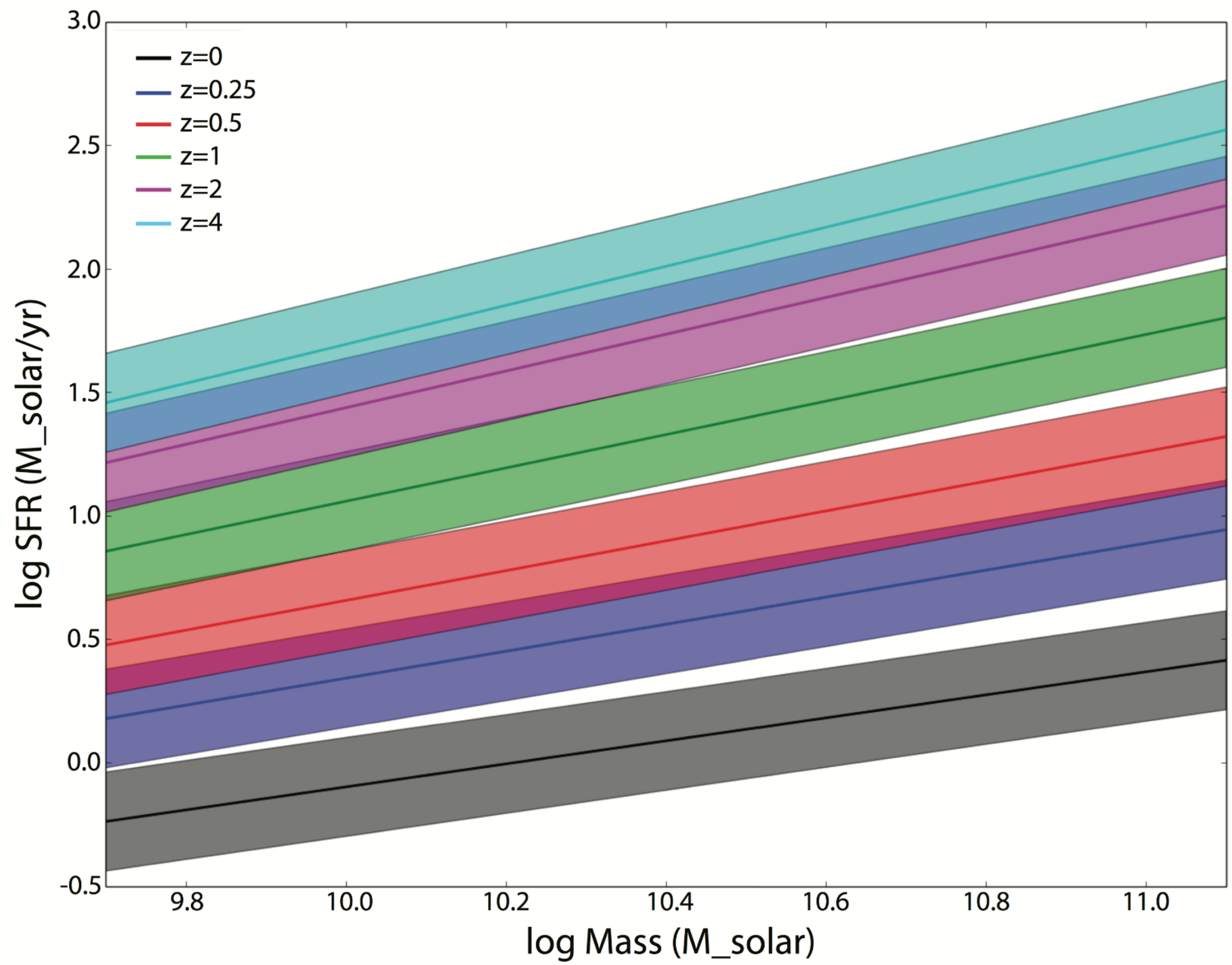
Greig & Mesinger (2017)
arXiv:1605.05374



Mason et al. (2017)
arXiv:11709.05356

EGA — Know: Star-Forming Main Sequence

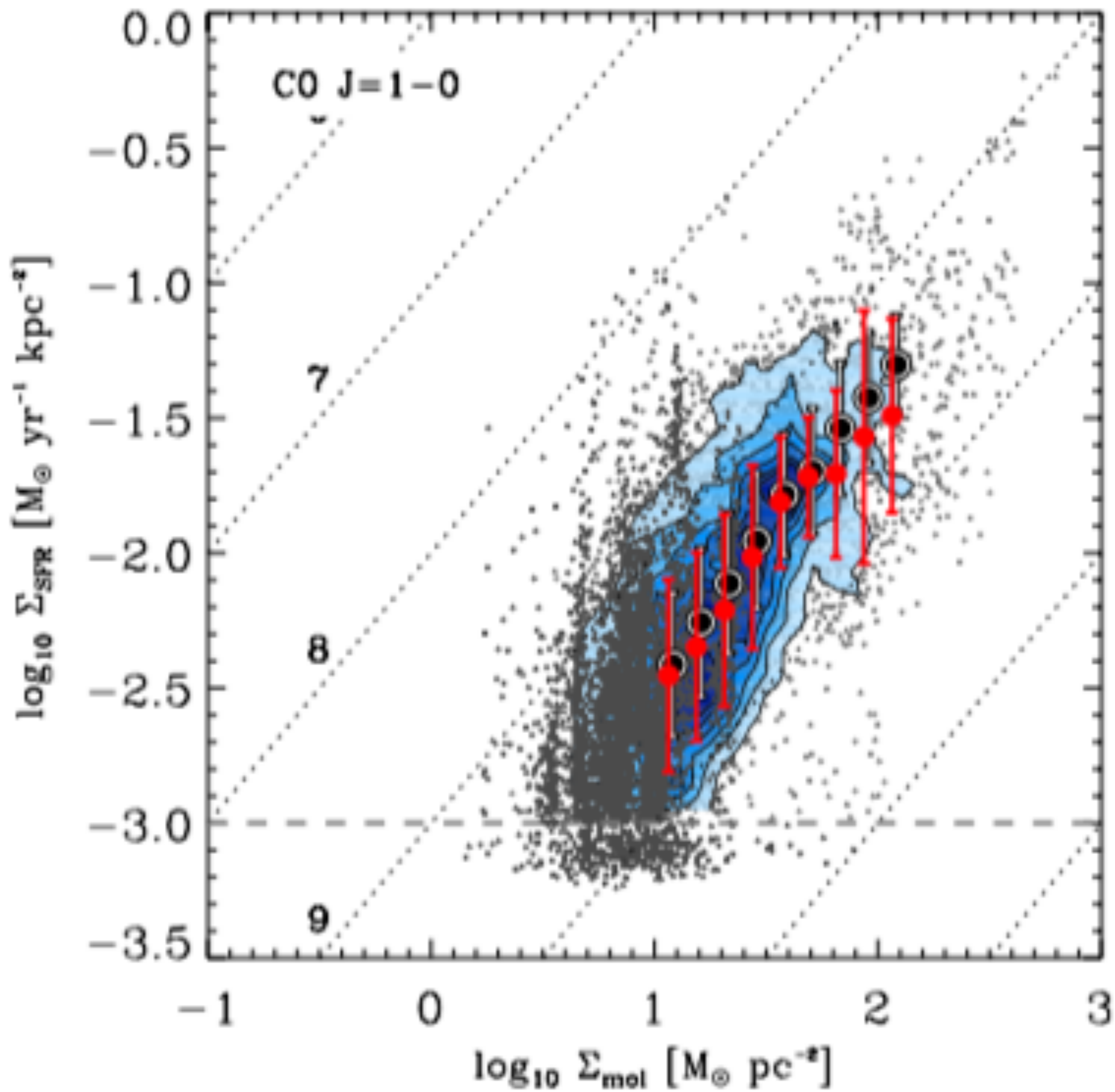
- Star-formation rate is a strong function of galaxy stellar-mass.
  - ➡Exceptions include starbursts (above), and quiescent (below).
- Power-law evolves strongly with redshift.



Speagle et al. (2014) — arXiv:1405.2041

EGA — Know: SFR / Molecular Gas Surface Densities Proportional

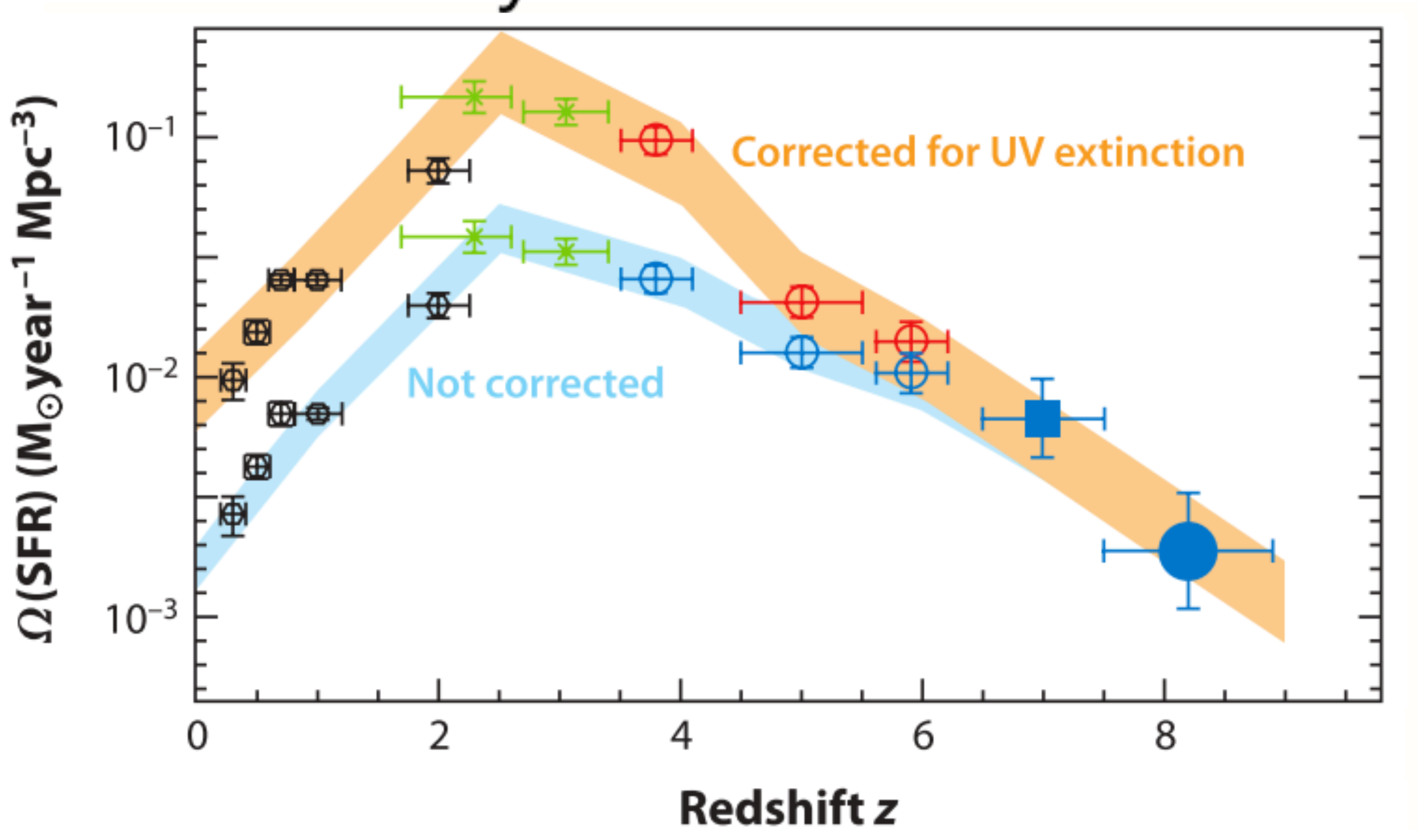
- Seen locally in detailed studies of resolved galaxies in HI and CO.
- Exhaustion of gas reservoirs may explain strong evolution of the star-forming main sequence.



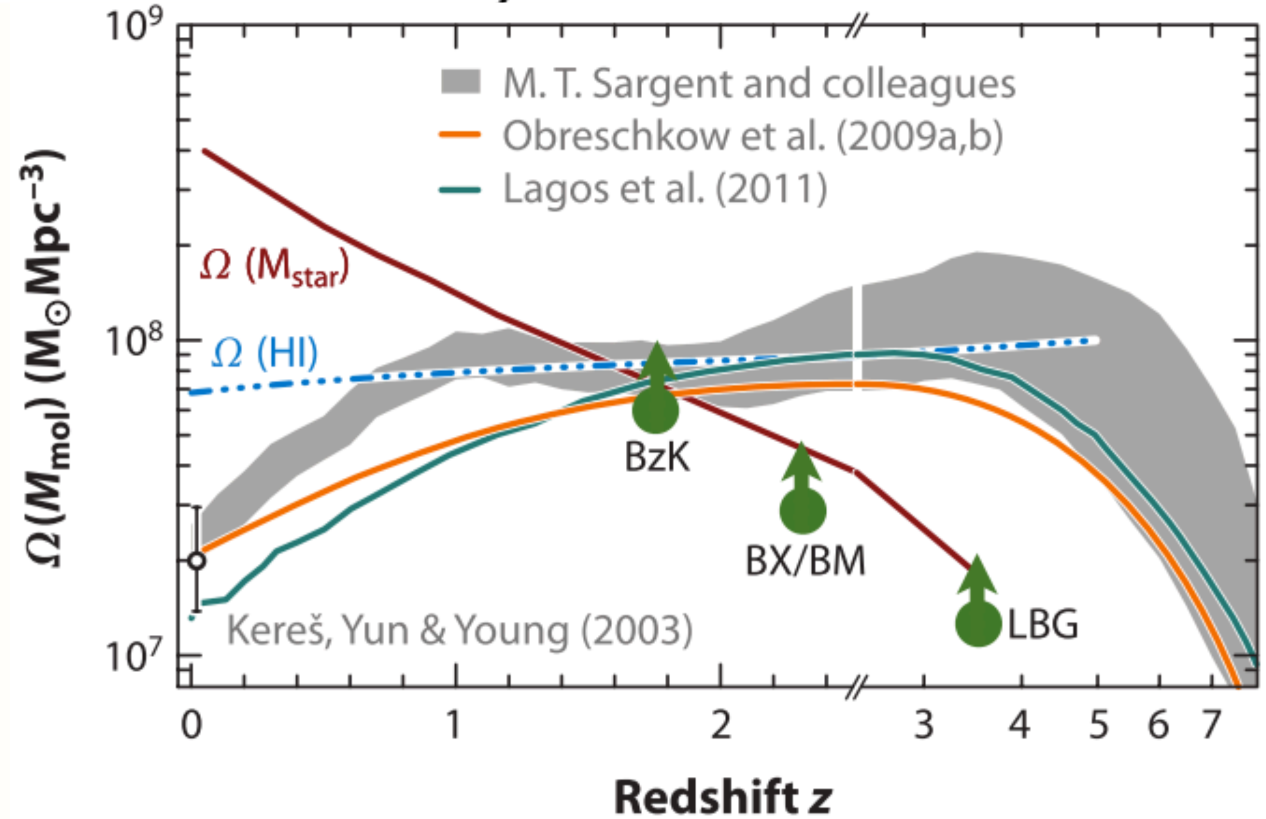
Leroy et al. (2013) — arXiv:1301.2328

EGA — Don't Know: Role of Gas in High-z Galaxy Assembly

History of Star Formation



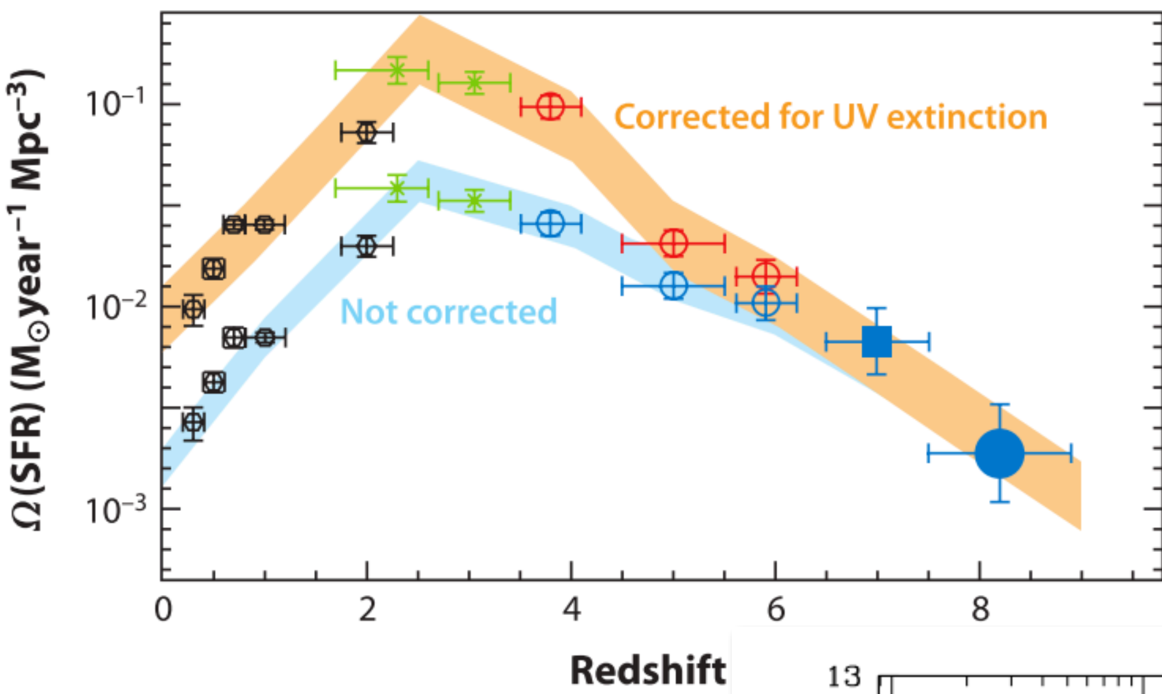
History of Gas Content



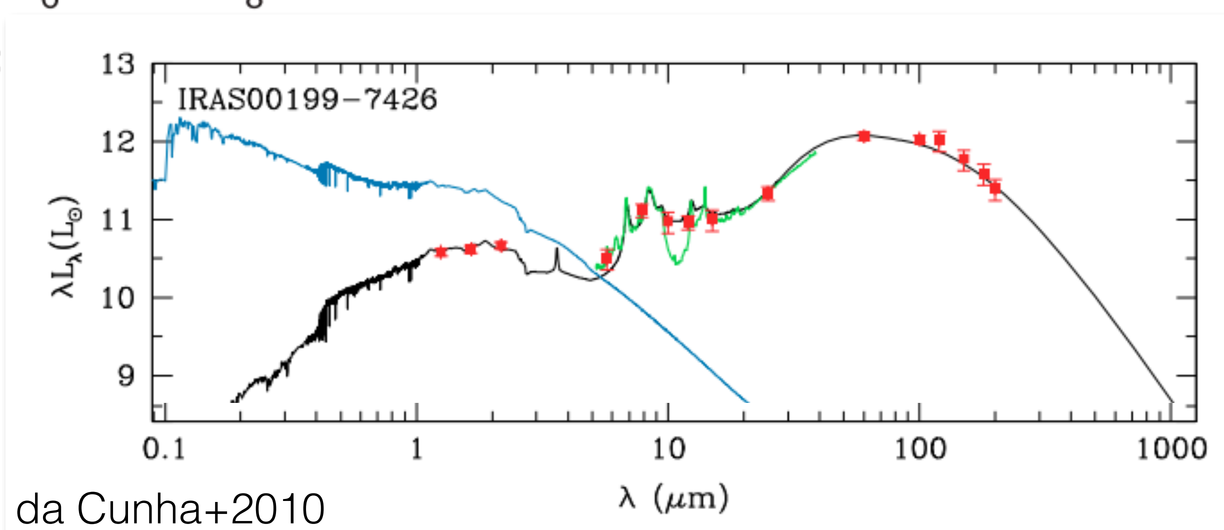
Carilli & Walter (2013) — arXiv:1301.0371

- To understand role of gas in star formation at all epochs, need to extend our knowledge of history of gas content to high-z.

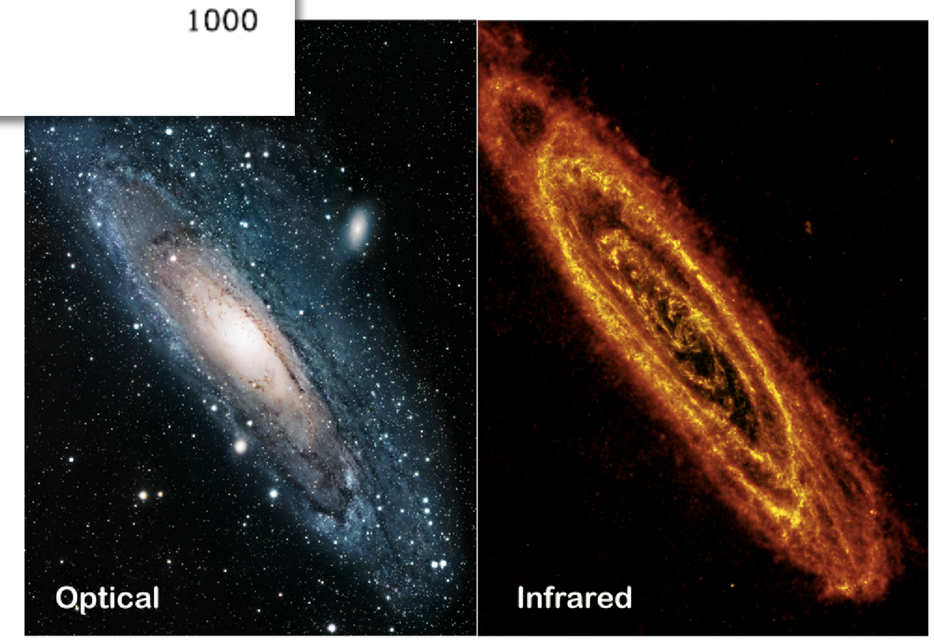
EGA — Don't know: High-z Contribution of Dusty Galaxies



- Infrared/Submillimeter emission reprocessed starlight by dust
- IR/Submm traces star formation



da Cunha+2010



- Why not determine SFRs by observe the dust directly, rather than correcting UV?

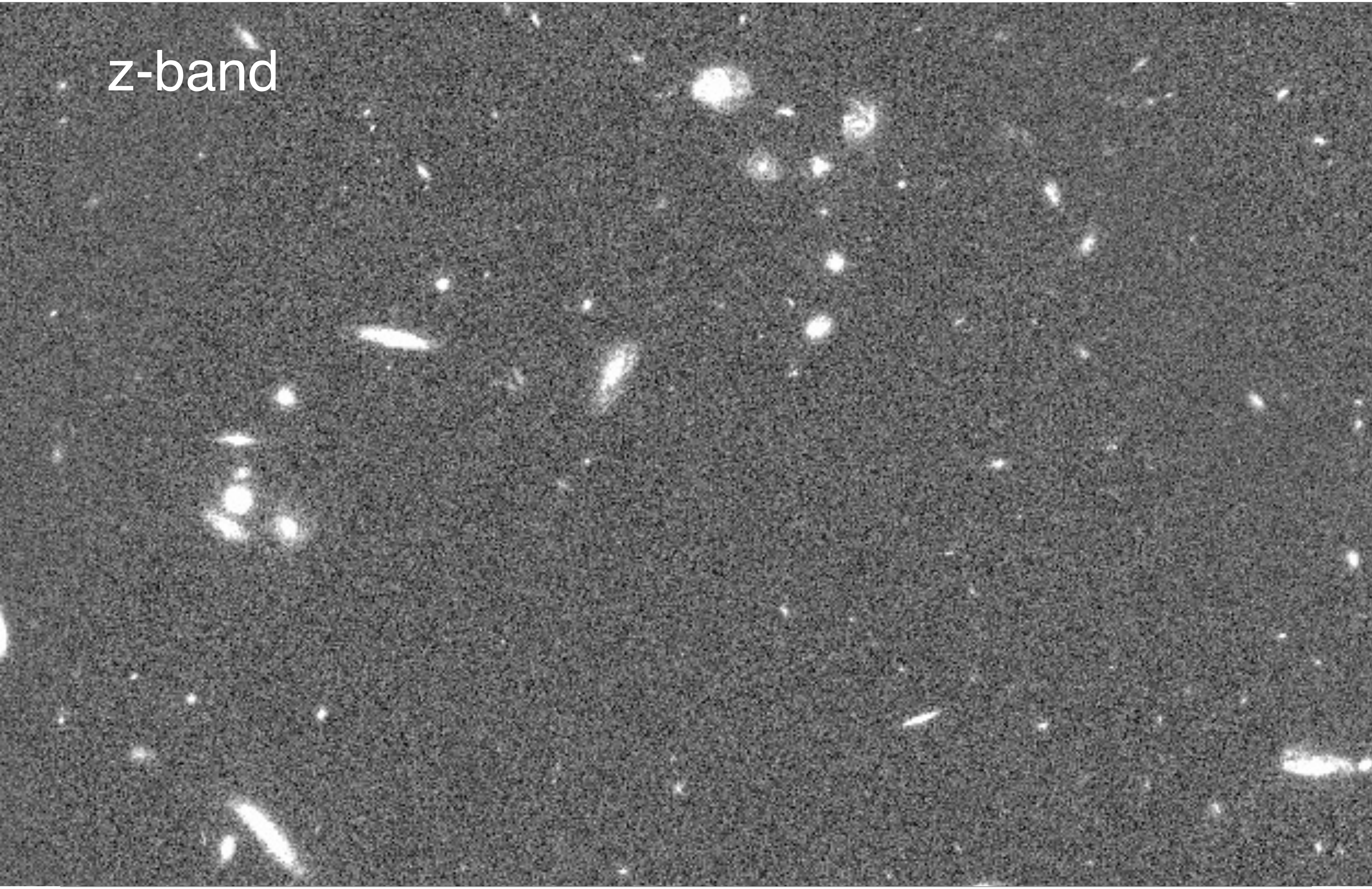
Early Universe: What We Know and What We Don't Know

	Know	Don't Know

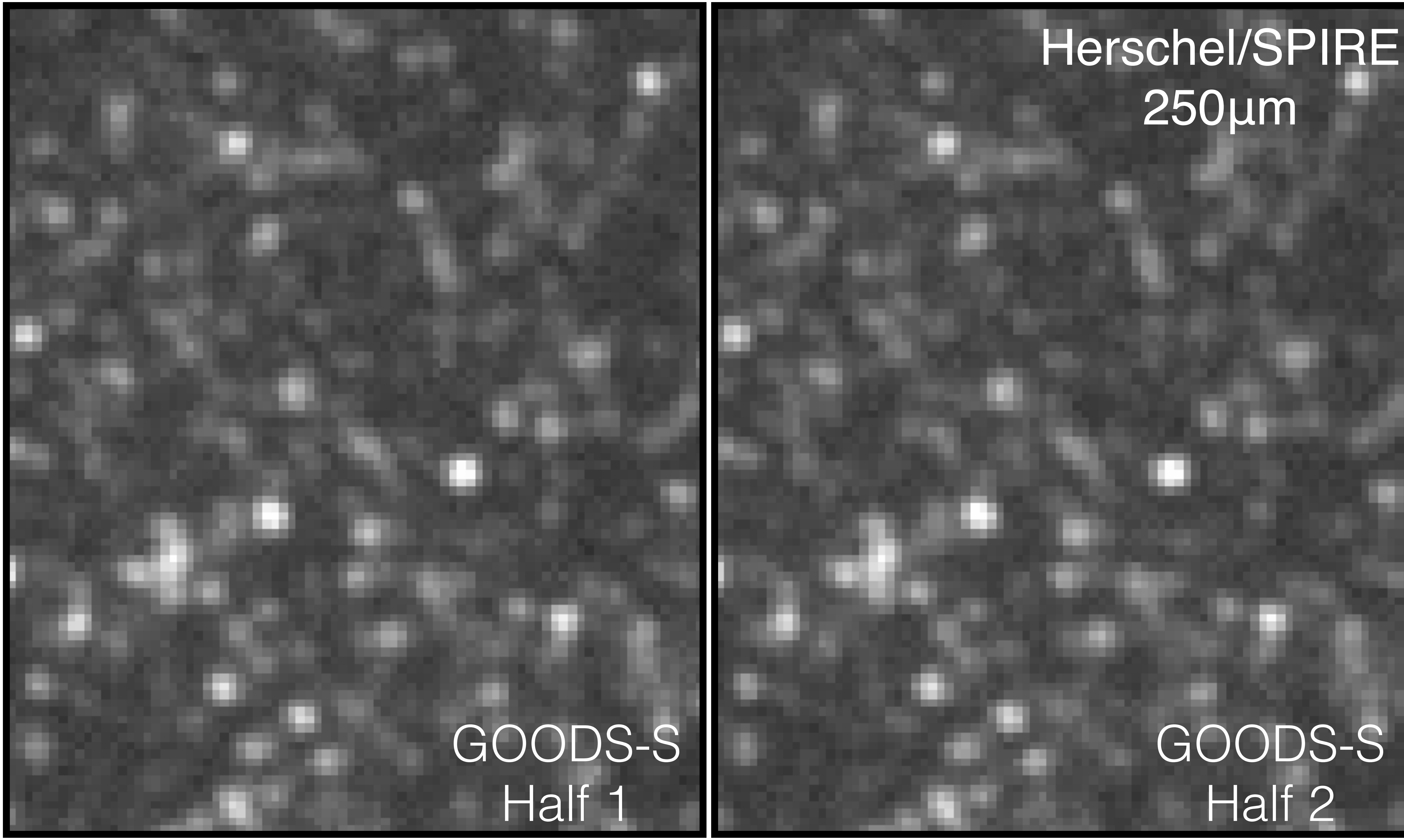
EoR	• Planck optical depth (τ = 0.065) puts instantaneous reionization at z = 8.8 +- 1.5
	• Reionization is Patchy: e.g., Fan+2006, Becker+2015
		• Details of Reionization:
		  • Start, duration.
		  • Sources; SFG, AGN, faint?
		• Faint-end slope of Luminosity Function at high-z
		• Where LF turns-over

EGA	• Star formation proportional to molecular gas surface density
	• Specific star-formation rate proportional to stellar mass (SF main sequence, MS)
	• MS evolves strongly with z
		• Molecular Gas Density at high-z, and its role in:
		  • peak halo-mass efficiency
		  • evolving main-sequence
		• Contribution of dusty galaxies to high-z SFRD

EGA — Challenge: Source Confusion

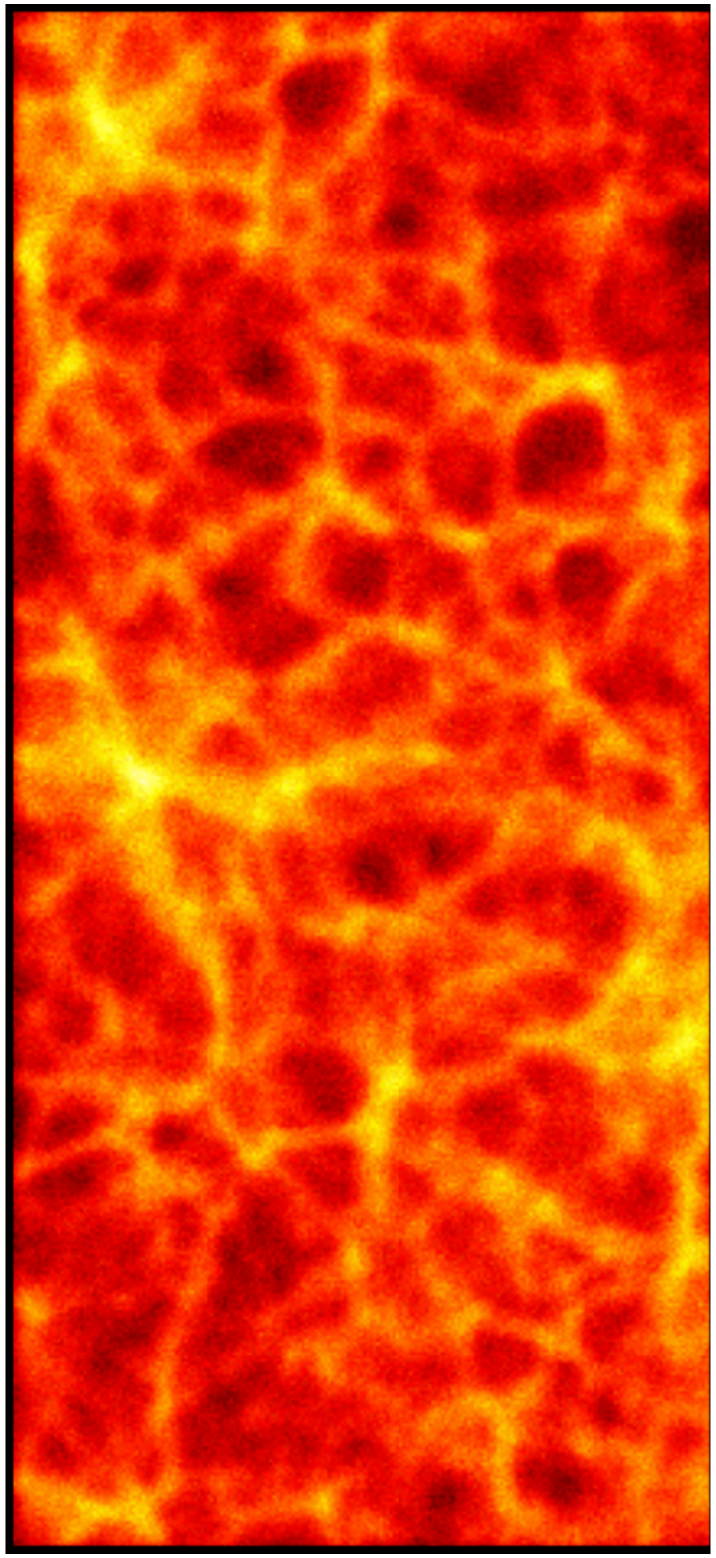


Solution: Embrace Statistical Methods



Embracing Statistical Methods

- Galaxies are *biased tracers* of the dark matter distribution.
- Usually want to know about the entire population, but we use what we can see: galaxies.
  - ➡ Depending on survey depth and wavelength, make up ~ 1 - 50% of the extragalactic background light; e.g., Dole+2006, Viero+2013
- Statistical methods aim to use the aggregate intensities of all the sources of emission.



Dore et al. (2015)

Embracing Statistical Methods

- Statistical Methods Include:
  - ➡N-point functions
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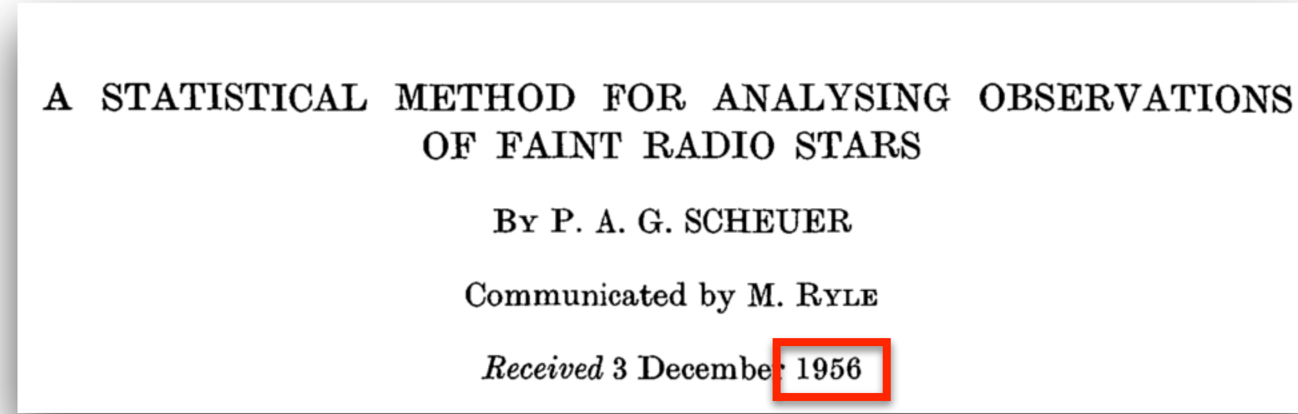
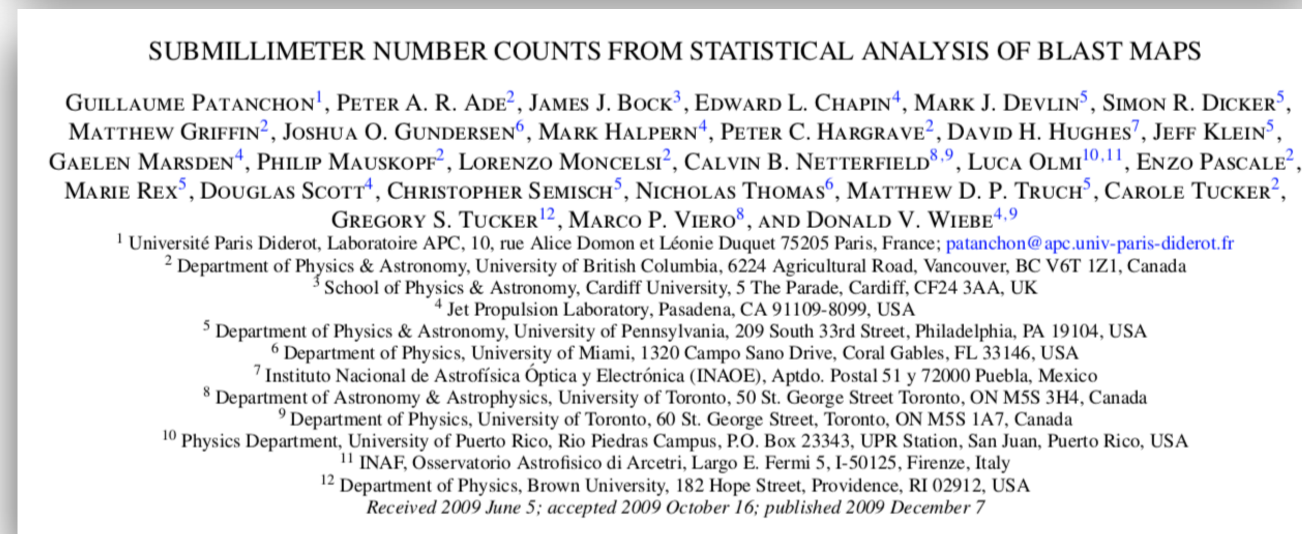


A STATISTICAL METHOD FOR ANALYSING OBSERVATIONS OF FAINT RADIO STARS

By P. A. G. SCHEUER

Communicated by M. RYLE

Received 3 December 1956



SUBMILLIMETER NUMBER COUNTS FROM STATISTICAL ANALYSIS OF BLAST MAPS

GUILLAUME PATANCHON[1], PETER A. R. ADE[2], JAMES J. BOCK[3], EDWARD L. CHAPIN[4], MARK J. DEVLIN[5], SIMON R. DICKER[5], MATTHEW GRIFFIN[2], JOSHUA O. GUNDERSEN[6], MARK HALPERN[4], PETER C. HARGRAVE[2], DAVID H. HUGHES[7], JEFF KLEIN[5], GAELEN MARSDEN[4], PHILIP MAUSKOPF[2], LORENZO MONCELSI[2], CALVIN B. NETTERFIELD[8,9], LUCA OLMI[10,11], ENZO PASCALE[2], MARIE REX[5], DOUGLAS SCOTT[4], CHRISTOPHER SEMISCH[5], NICHOLAS THOMAS[6], MATTHEW D. P. TRUCH[5], CAROLE TUCKER[2], GREGORY S. TUCKER[12], MARCO P. VIERO[8], AND DONALD V. WIEBE[4,9]

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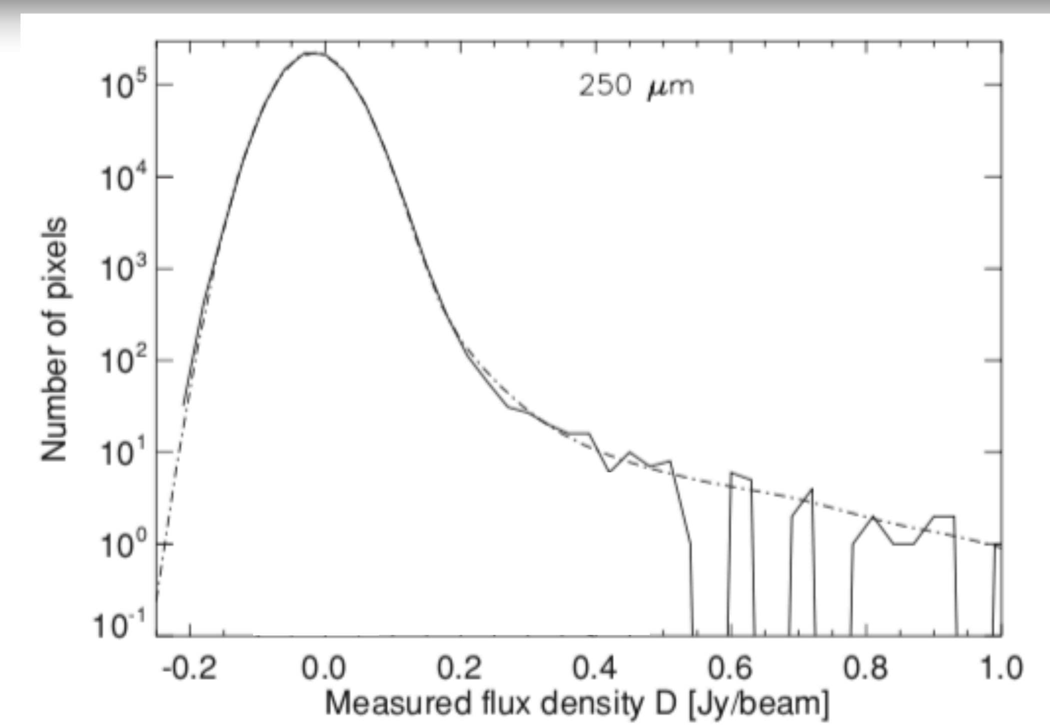

Embracing Statistical Methods

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THE THREE-DIMENSIONAL POWER SPECTRUM OF GALAXIES FROM THE SLOAN DIGITAL SKY SURVEY

Max Tegmark,[1] Michael R. Blanton,[2] Michael A. Strauss,[3] Fiona Hoyle,[4] David Schlegel,[3] Roman Scoccimarro,[2] Michael S. Vogeley,[4] David H. Weinberg,[5] Idit Zehavi,[6] Andreas Berlind,[6] Tamás Budavari,[7] Andrew Connolly,[8] Daniel J. Eisenstein,[9] Douglas Finkbeiner,[3] Joshua A. Frieman,[6,10] James E. Gunn,[3] Andrew J. S. Hamilton,[11] Lam Hui,[10] Bhuvnesh Jain,[1] David Johnston,[6,10] Stephen Kent,[10] Huan Lin,[10] Reiko Nakajima,[1] Robert C. Nichol,[12] Jeremiah P. Ostriker,[3] Adrian Pope,[7] Ryan Scranton,[8] Uroš Seljak,[3] Ravi K. Sheth,[8] Albert Stebbins,[10] Alexander S. Szalay,[7] István Szapudi,[13] Licia Verde,[3] Yongzhong Xu,[1] James Annis,[10] Neta A. Bahcall,[3] J. Brinkmann,[14] Scott Burles,[15] Francisco J. Castander,[16] Istvan Csabai,[7] Jon Loveday,[17] Mamoru Doi,[18] Masataka Fukugita,[18] J. Richard Gott III,[3] Greg Hennessy,[19] David W. Hogg,[2] Željko Ivezić,[3] Gillian R. Knapp,[3] Don Q. Lamb,[6] Brian C. Lee,[10] Robert H. Lupton,[3] Timothy A. McKay,[20] Peter Kunszt,[7] Jeffrey A. Munn,[19] Liam O'Connell,[17] John Peoples,[10] Jeffrey R. Pier,[19] Michael Richmond,[21] Constance Rockosi,[6] Donald P. Schneider,[22] Christopher Stoughton,[10] Douglas L. Tucker,[10] Daniel E. Vanden Berk,[8] Brian Yanny,[10] and Donald G. York[6,23]
(For the SDSS Collaboration)

Received 2003 June 18; accepted 2003 December 17

ABSTRACT

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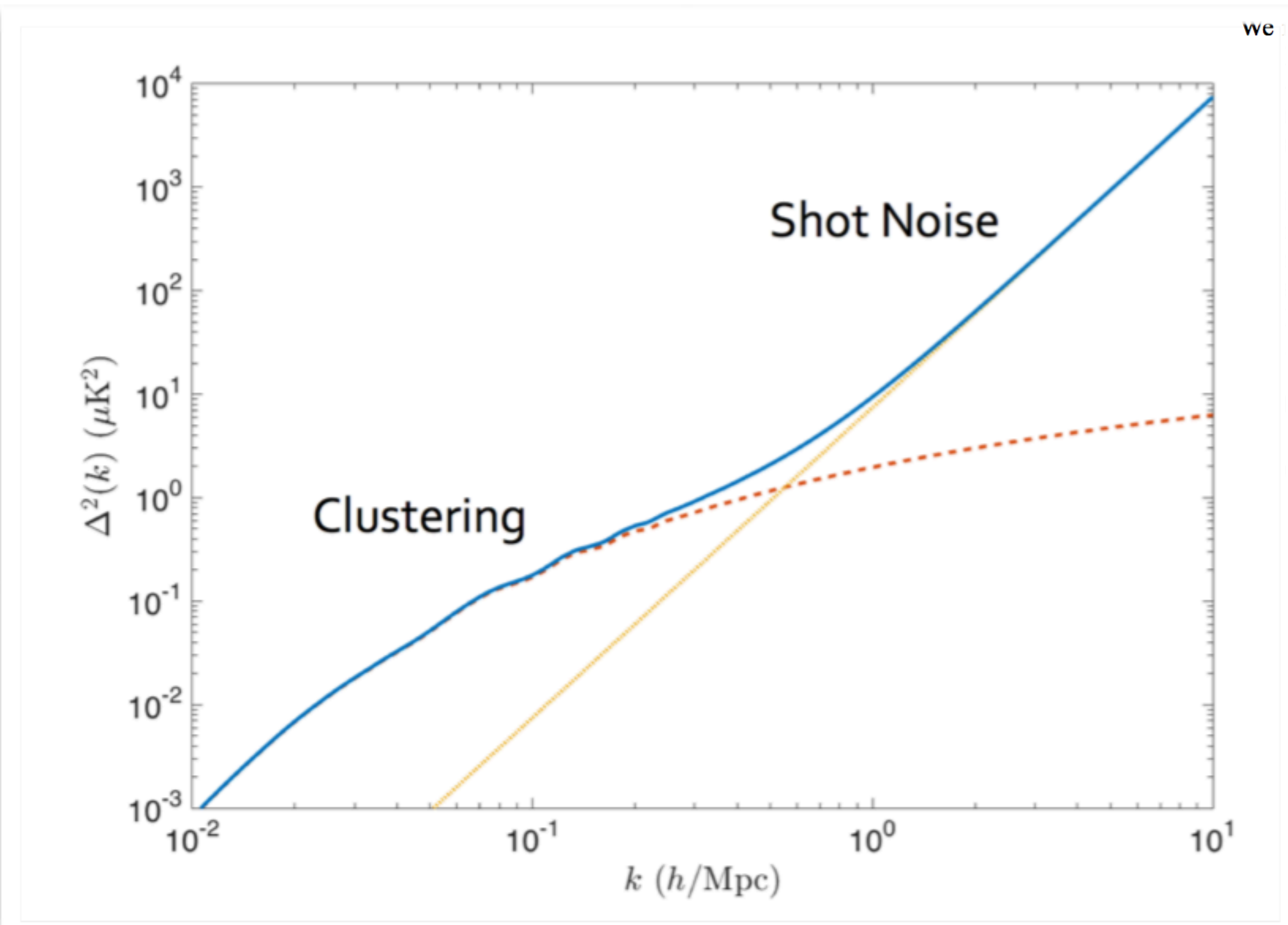

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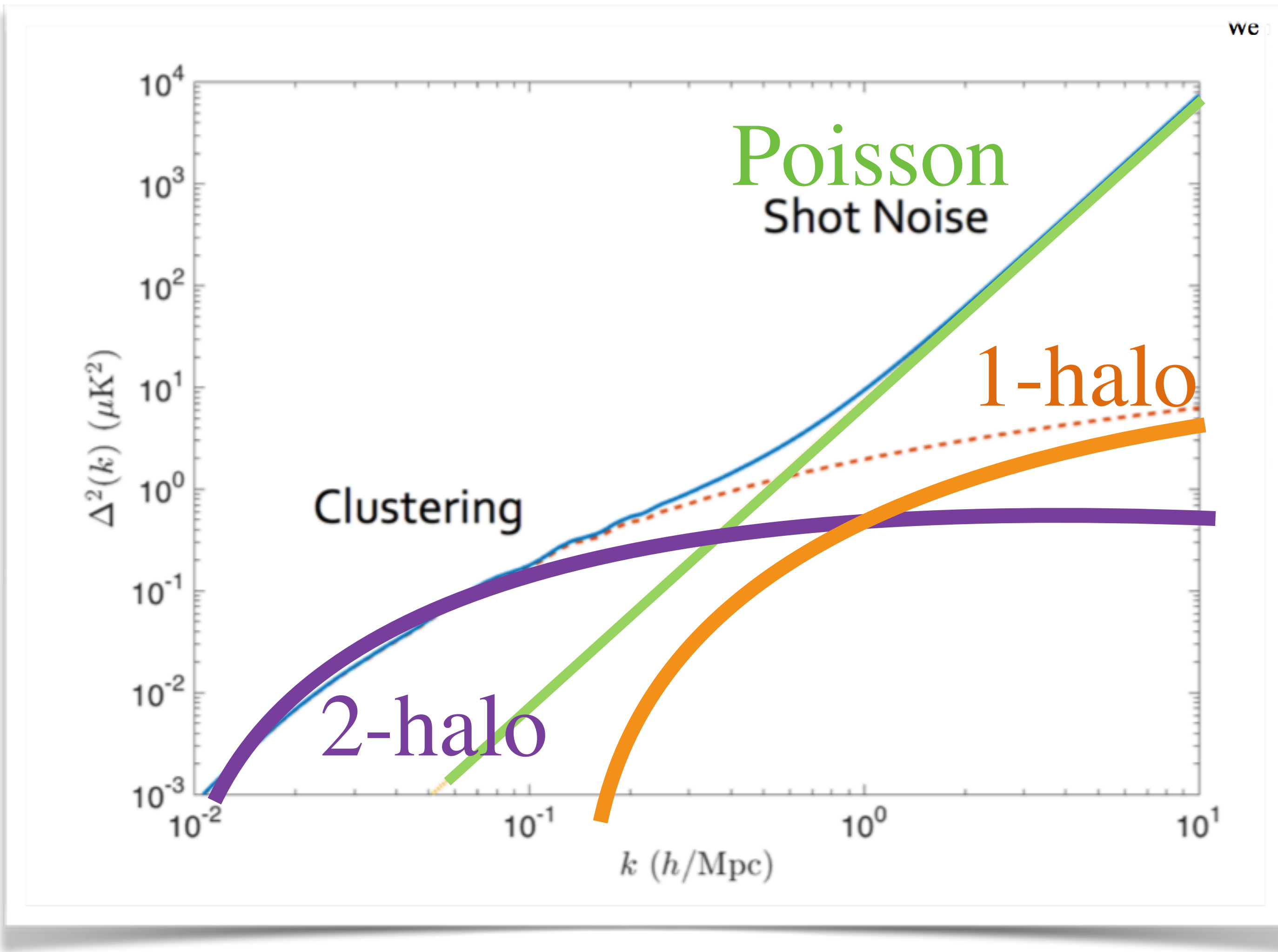

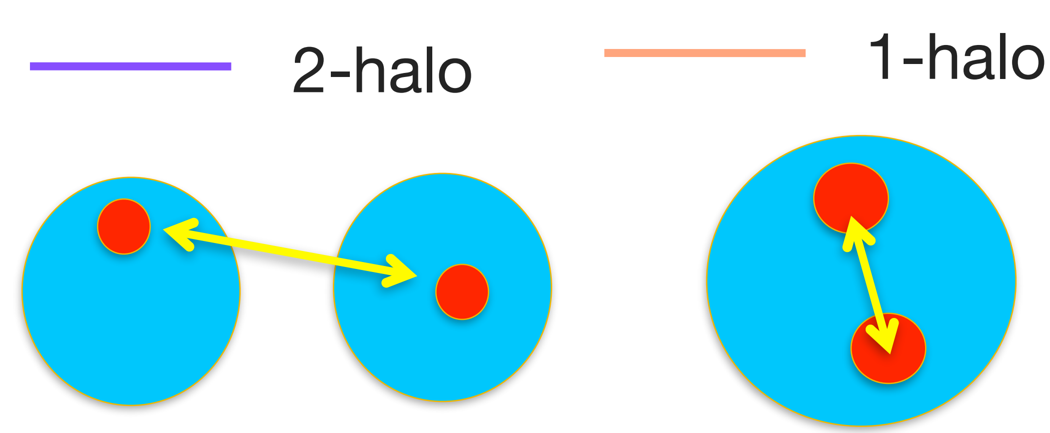

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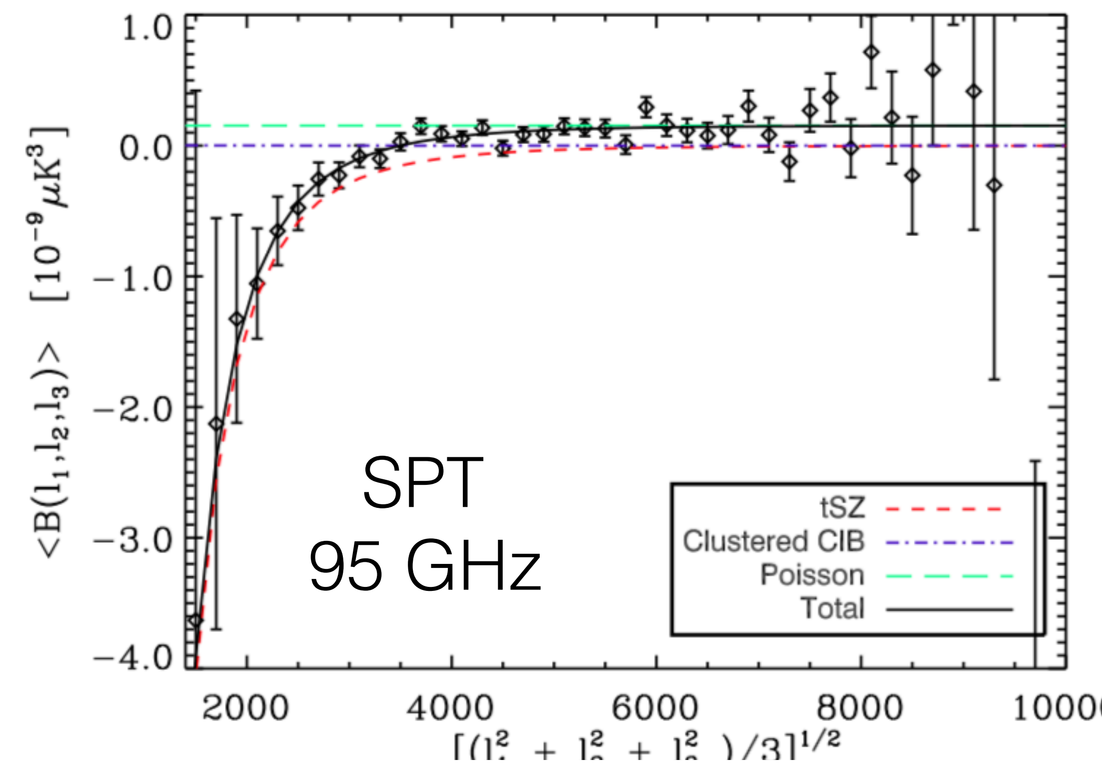

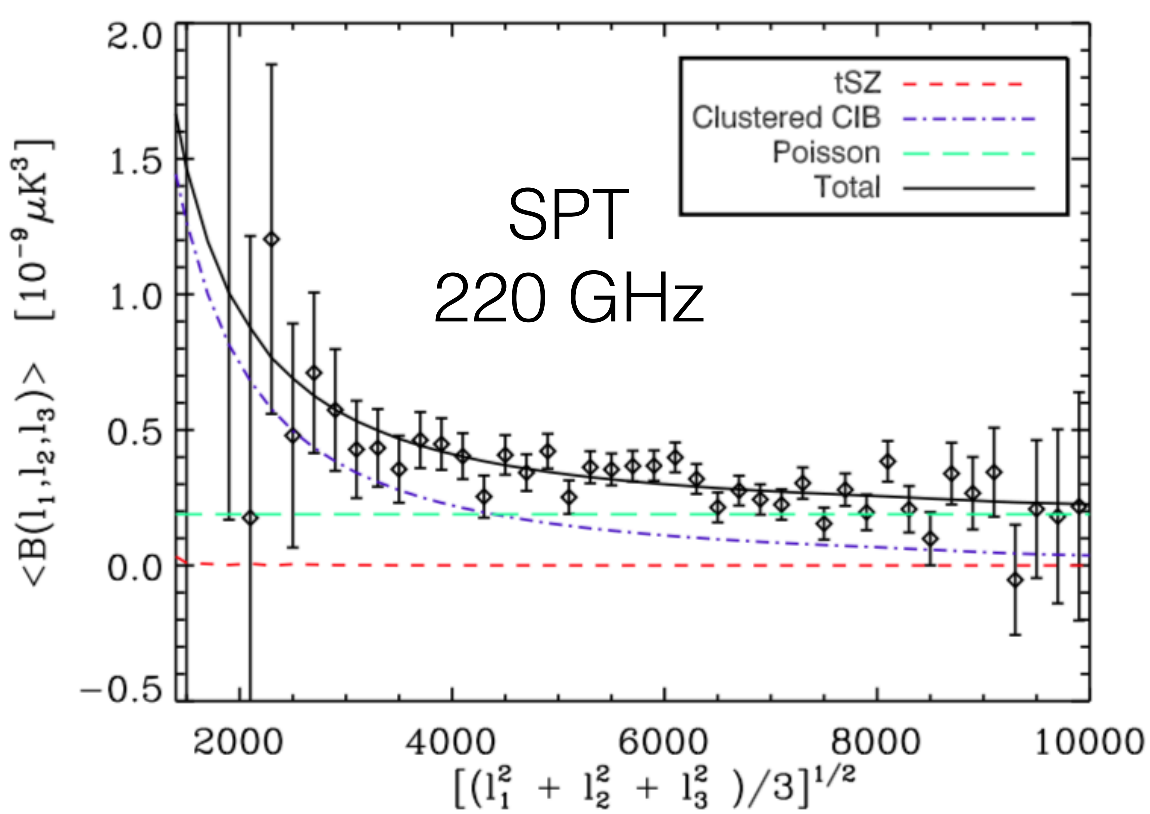

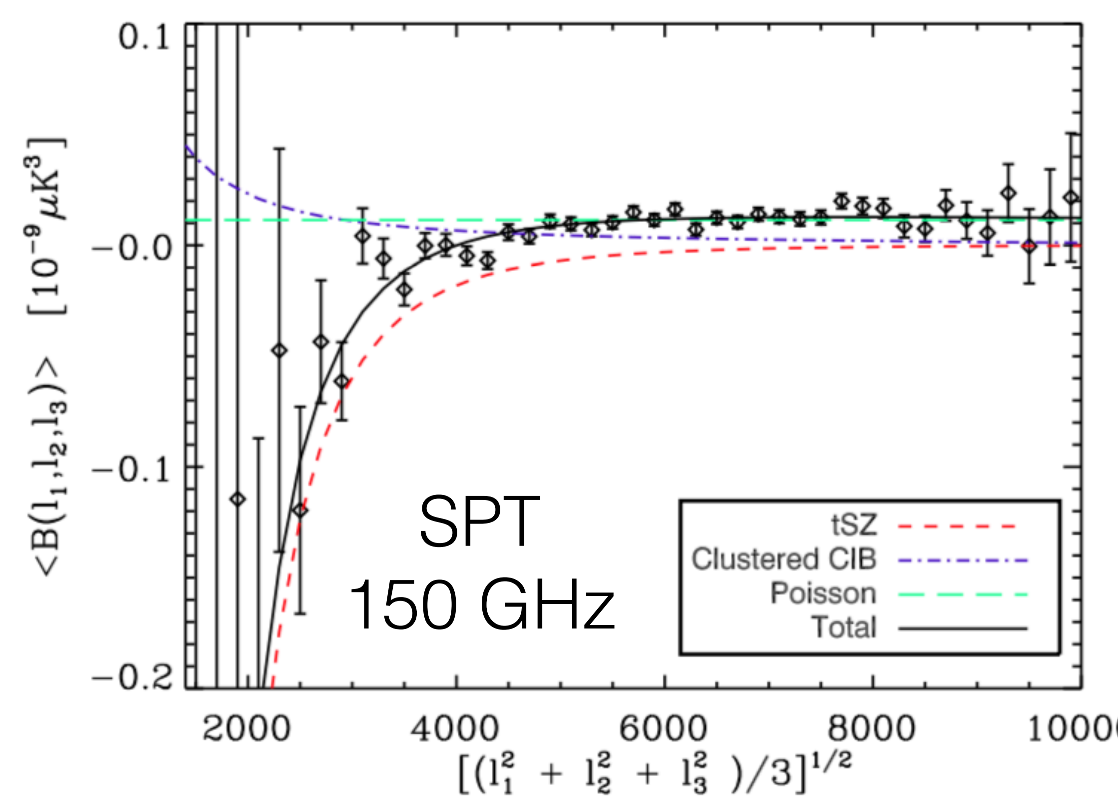

Crawford et al. (2014)

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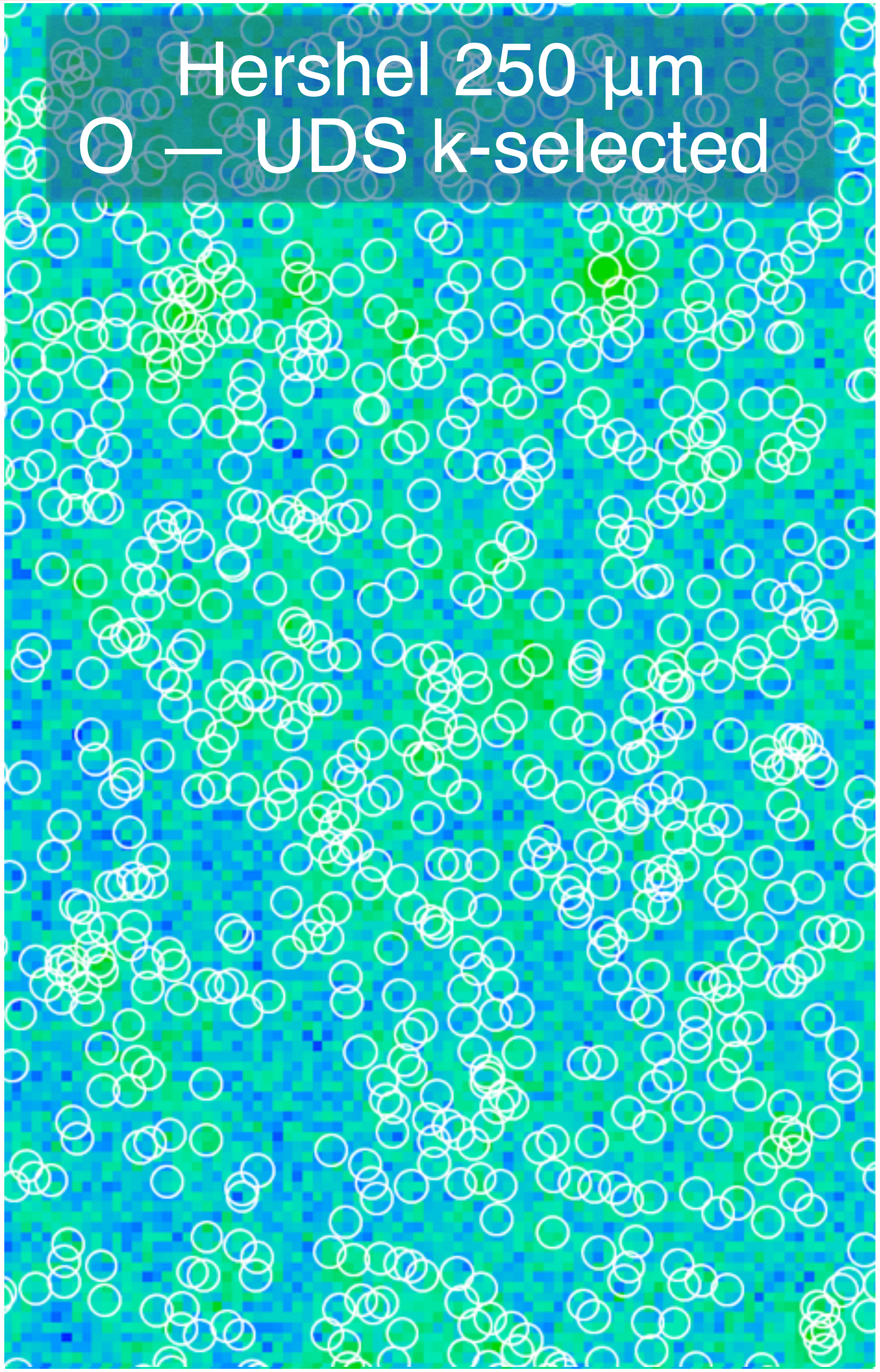
    - Thumbnail (2-pt function catalog-pixels)



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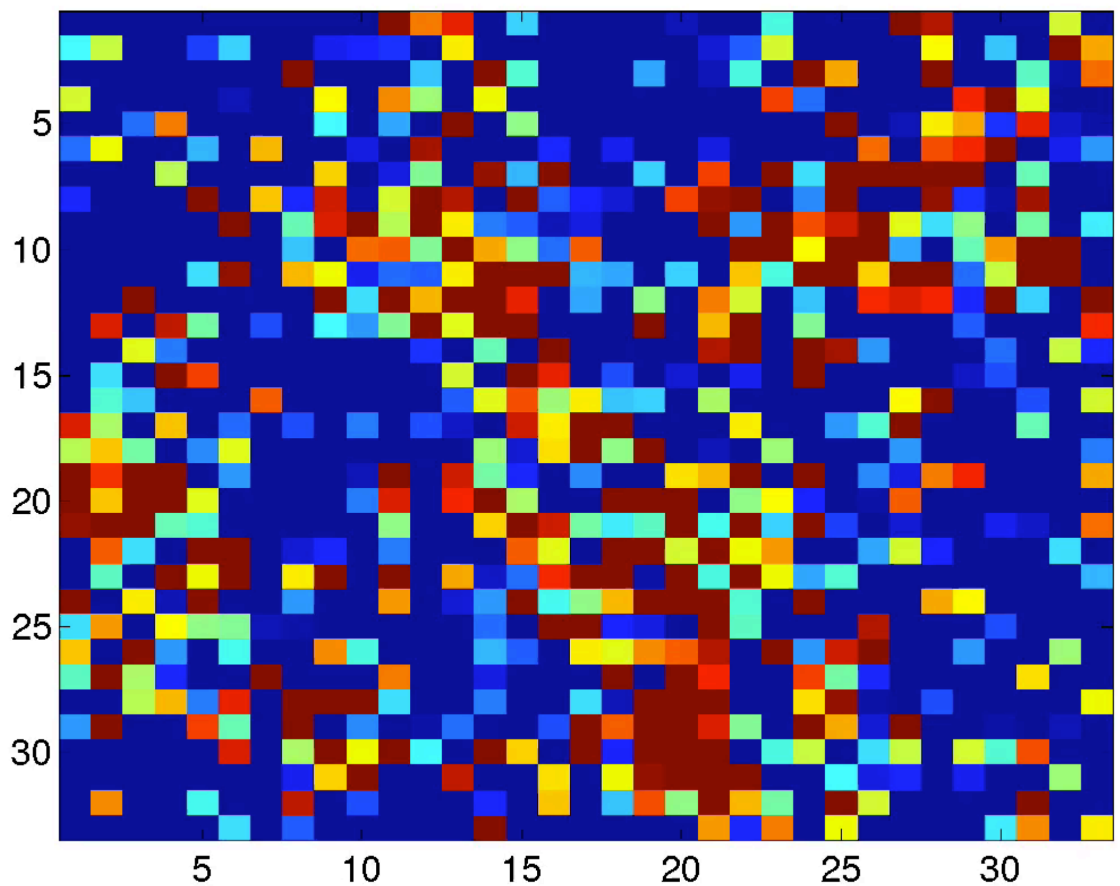

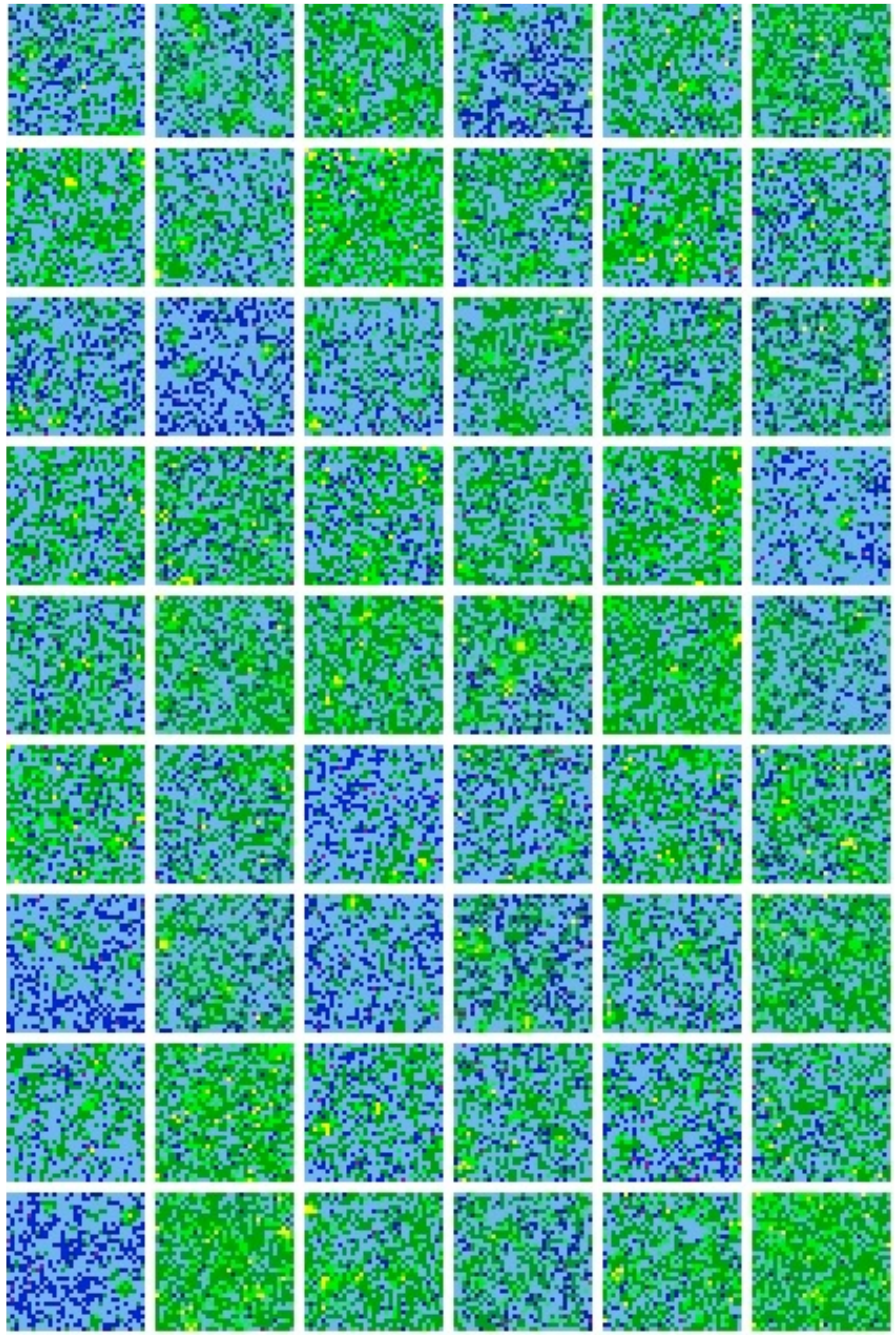

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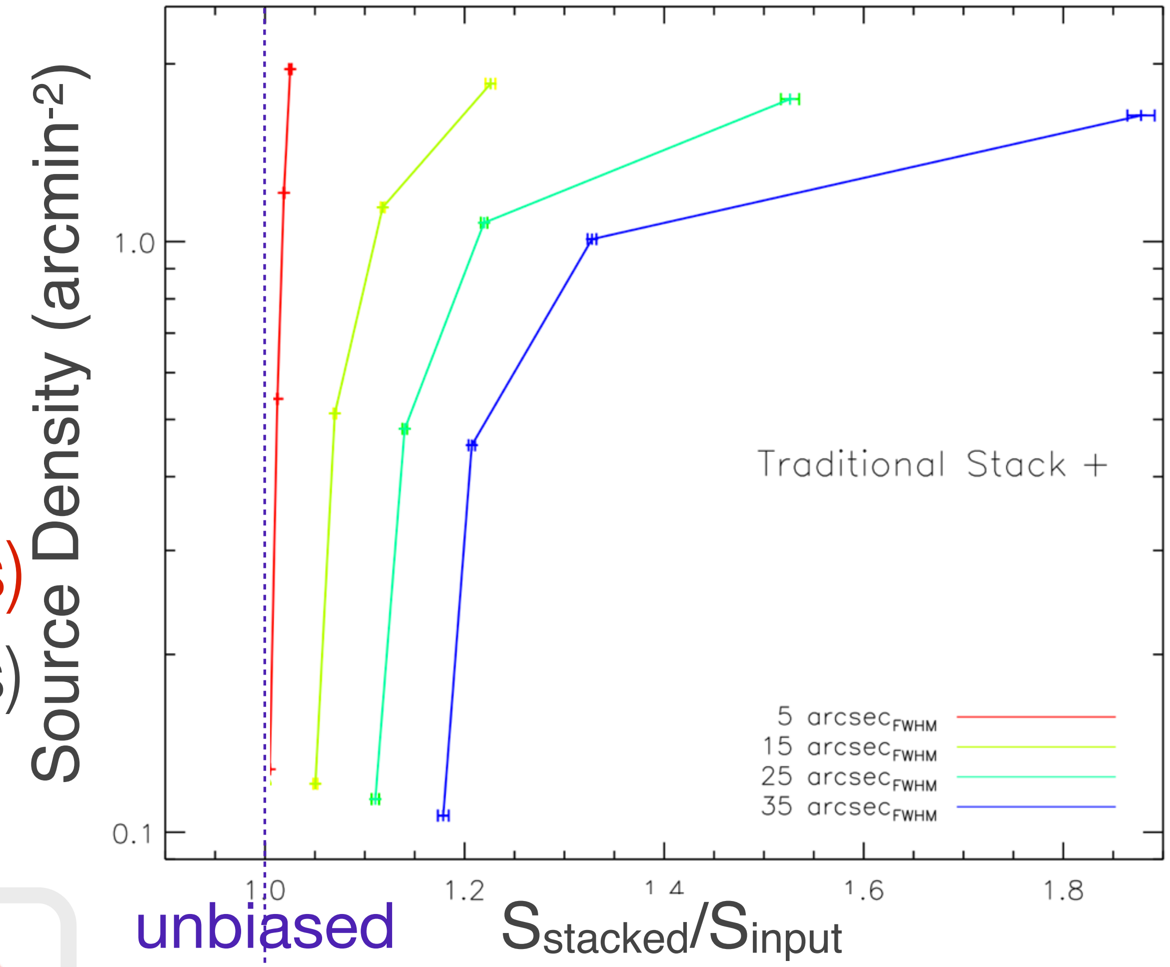
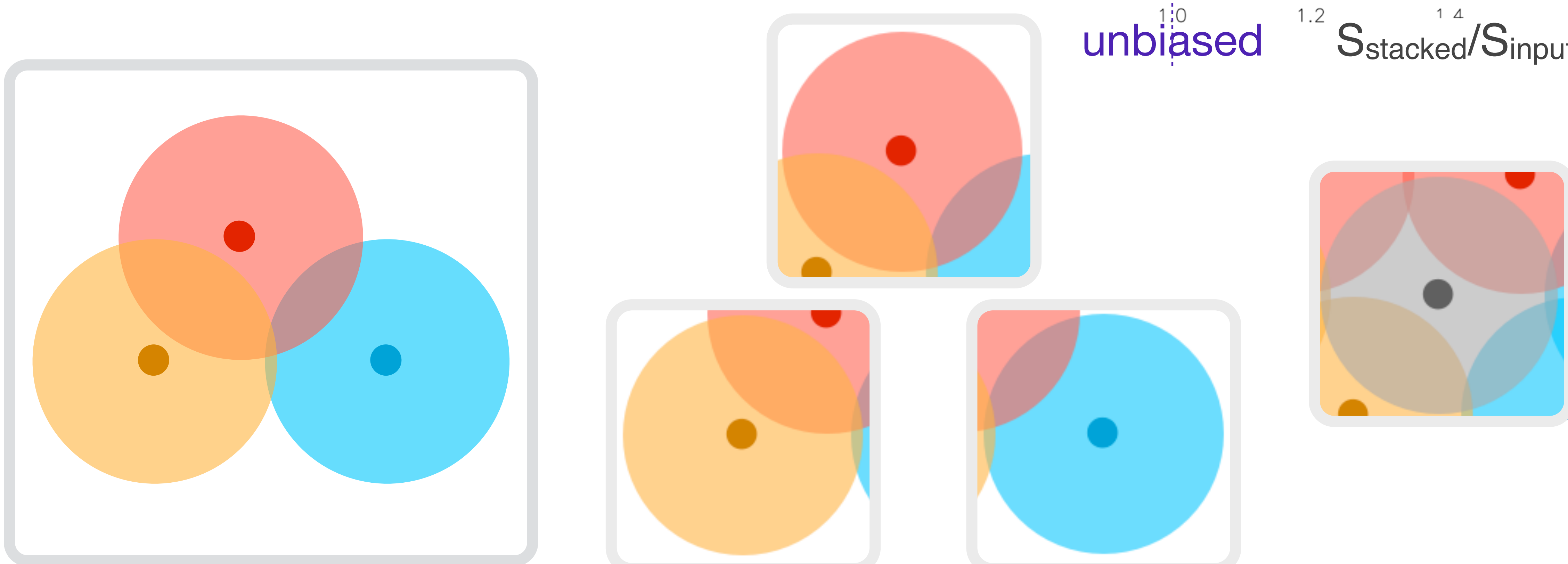
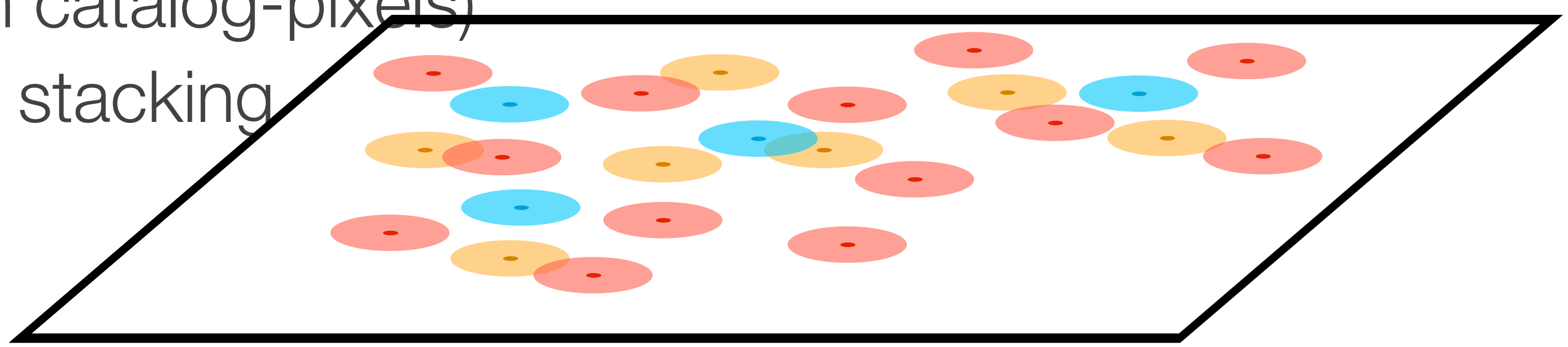




Embracing Statistical Methods

- Statistical Methods Include:
  - ➡N-point functions
    - 1-point, i.e., the histogram/P(D)
    - 2-point, i.e., the power spectrum
    - 3-point, i.e., bi-spectrum (skewness)
  - ➡Stacking (i.e. Covariance with Catalogs)
    - Thumbnail (2-pt function catalog-pixels)
    - SIMSTACK — unbiased stacking algorithm



Viero et al. 2013b — arXiv:1304.0446

Embracing Statistical Methods

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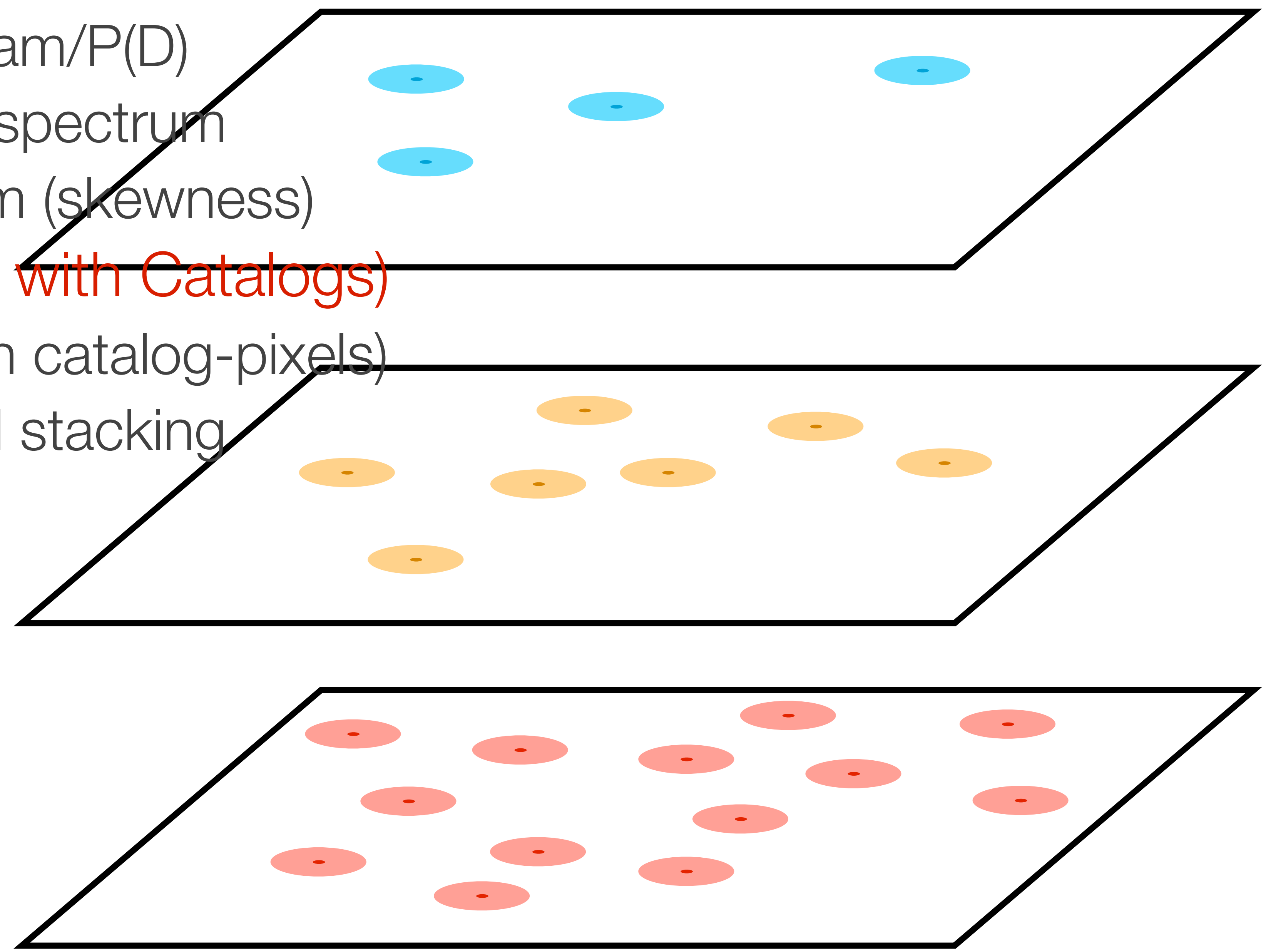
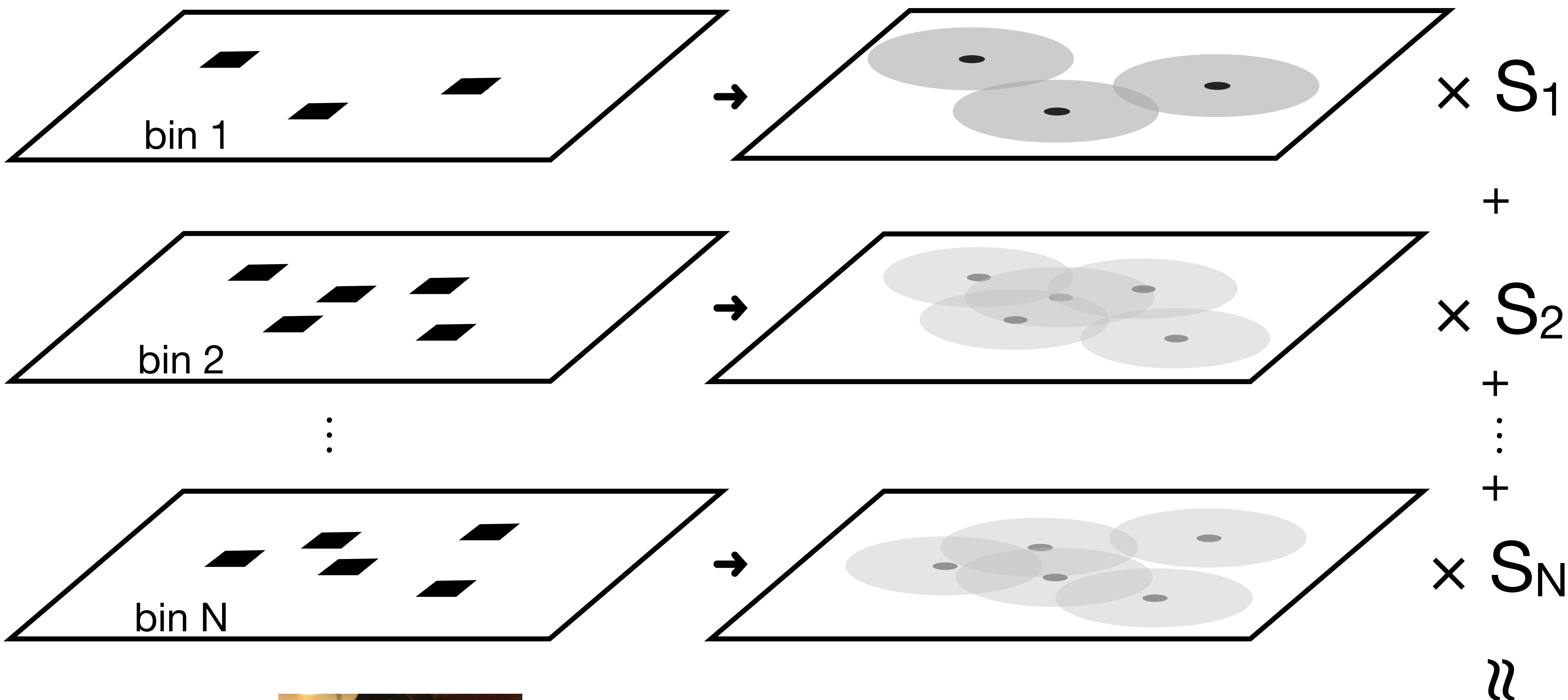
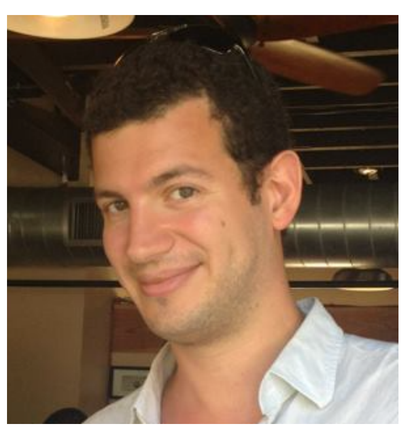


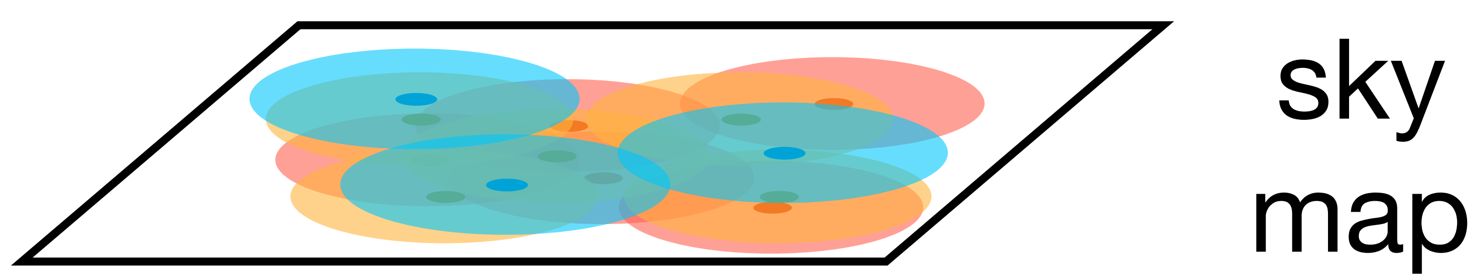
Viero et al. 2013b — arXiv:1304.0446

SIMSTACK — Unbiased Stacking Algorithm



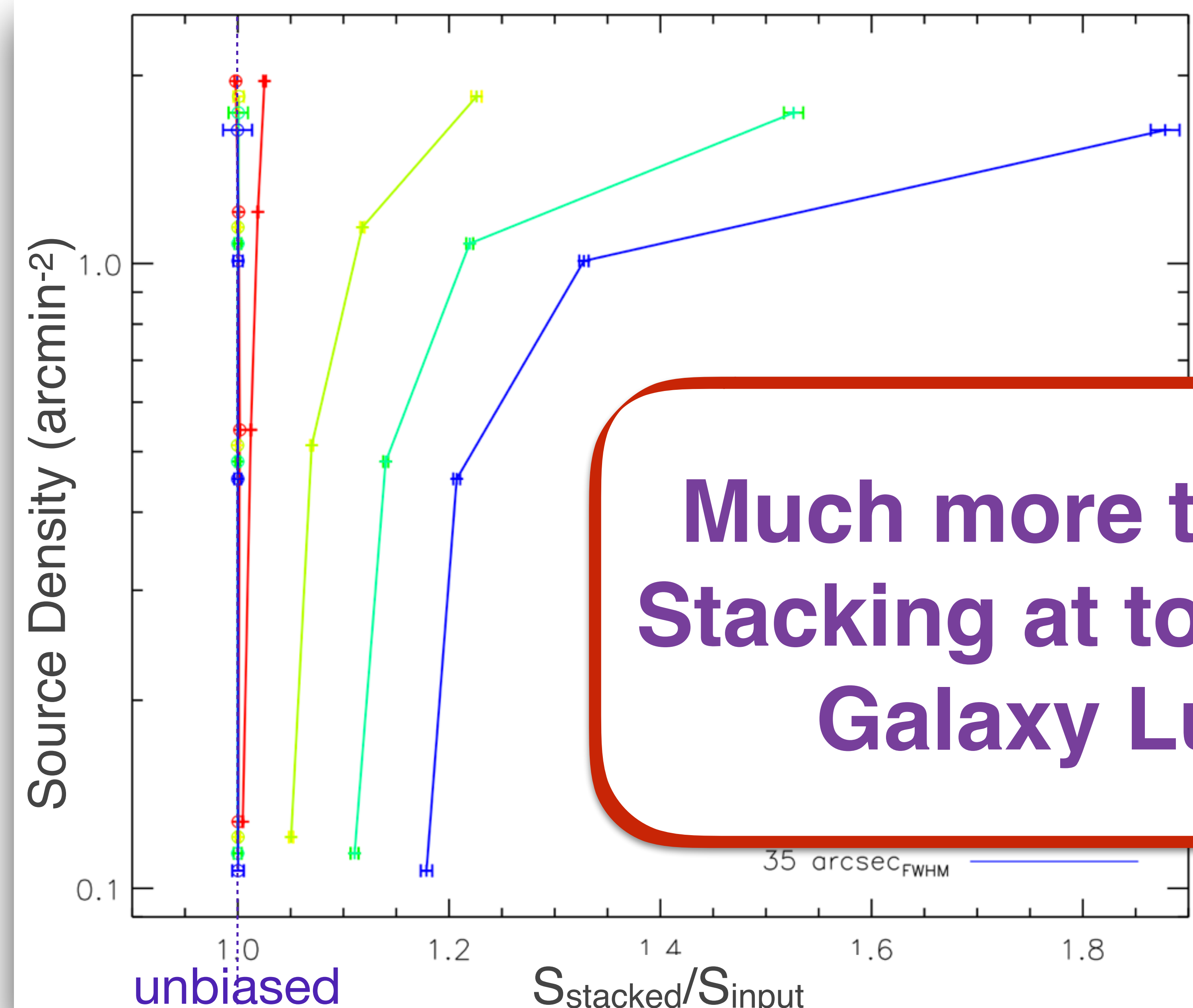
Formalism developed w/ Lorenzo Moncelsi (Caltech)

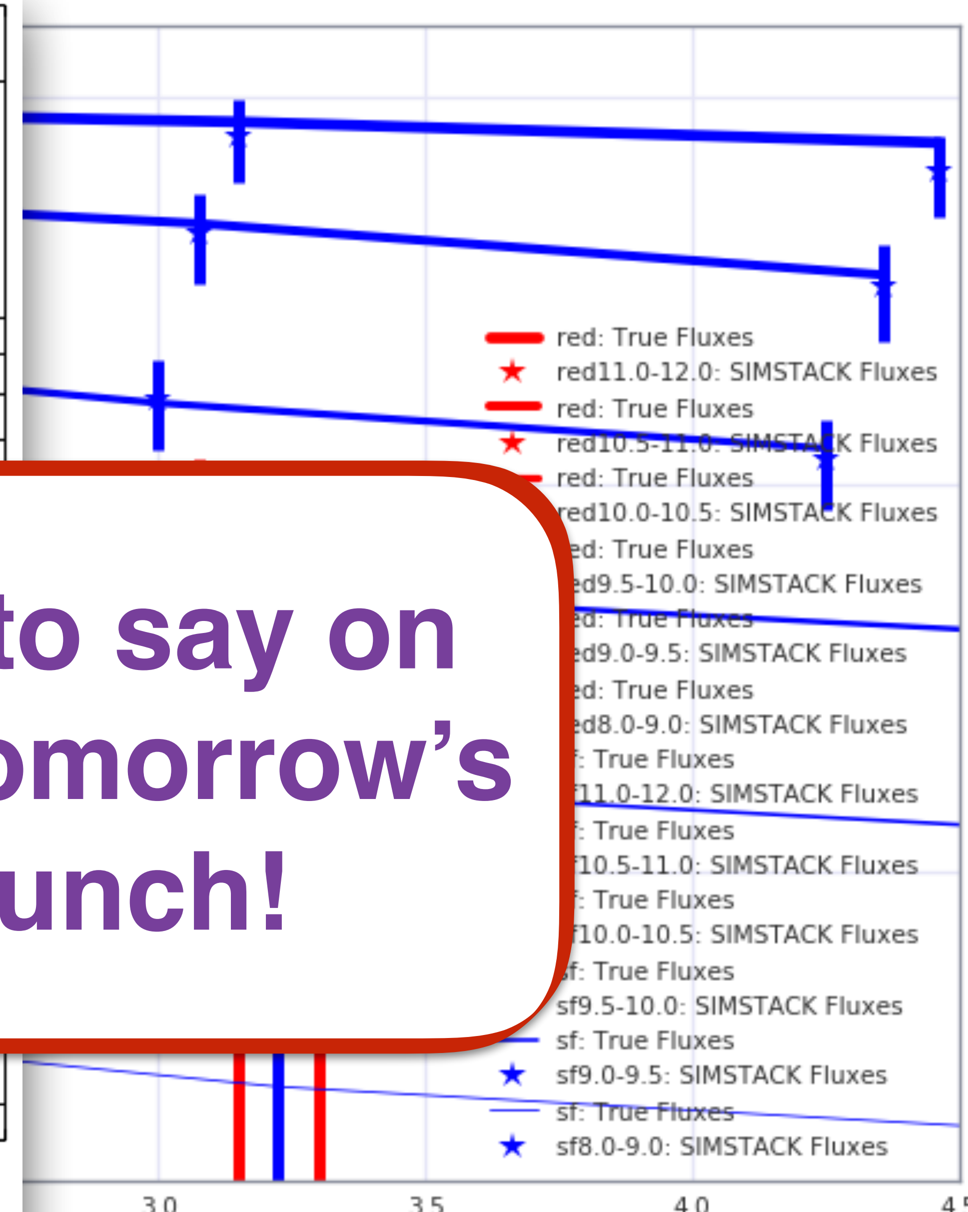




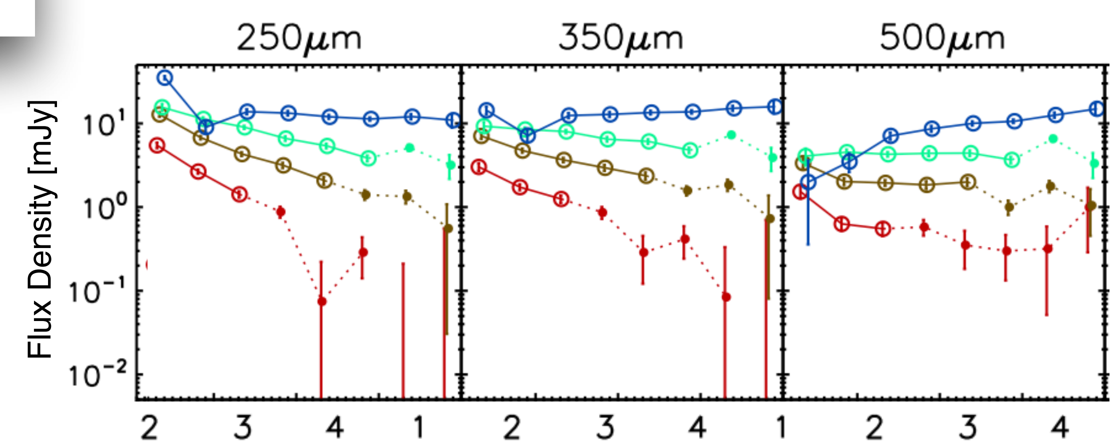
Viero et al. 2013b — arXiv:1304.0446
Python Code at https://github.com/marcoviero/simstack

Embracing Statistical Methods





Much more to say on Stacking at tomorrow's Galaxy Lunch!



Viero et al. 2013b — arXiv:1304.0446

Simulations made using SIDES model

Bethermin et al. 2017 — arXiv:1703.08795

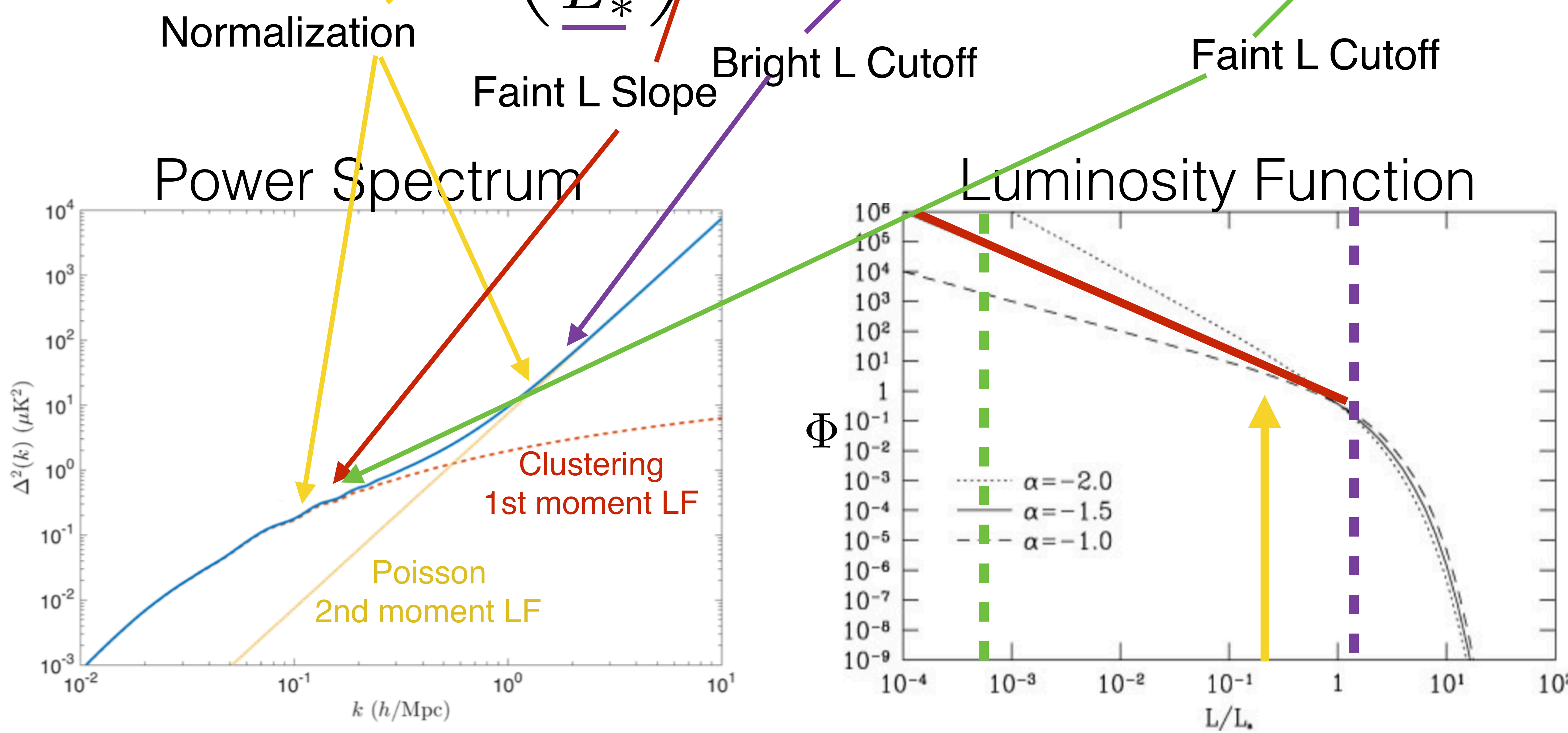
SIMSTACK code publicly available

https://github.com/marcoviero/simstack

Embracing Statistical Methods

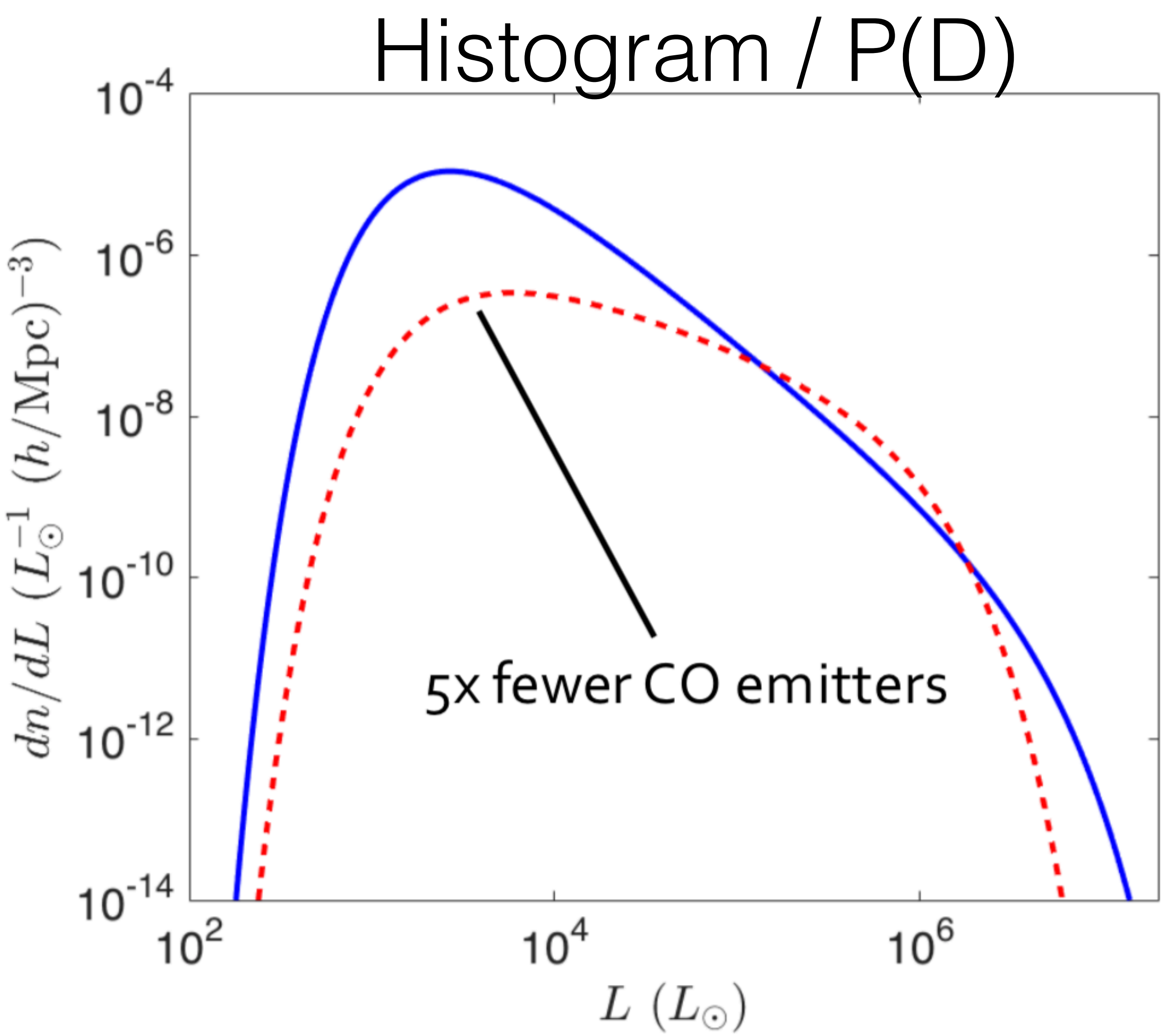
- Statistically-based Measurements Map to Physical Distributions
  - e.g., the Power Spectrum to the Luminosity Function as:

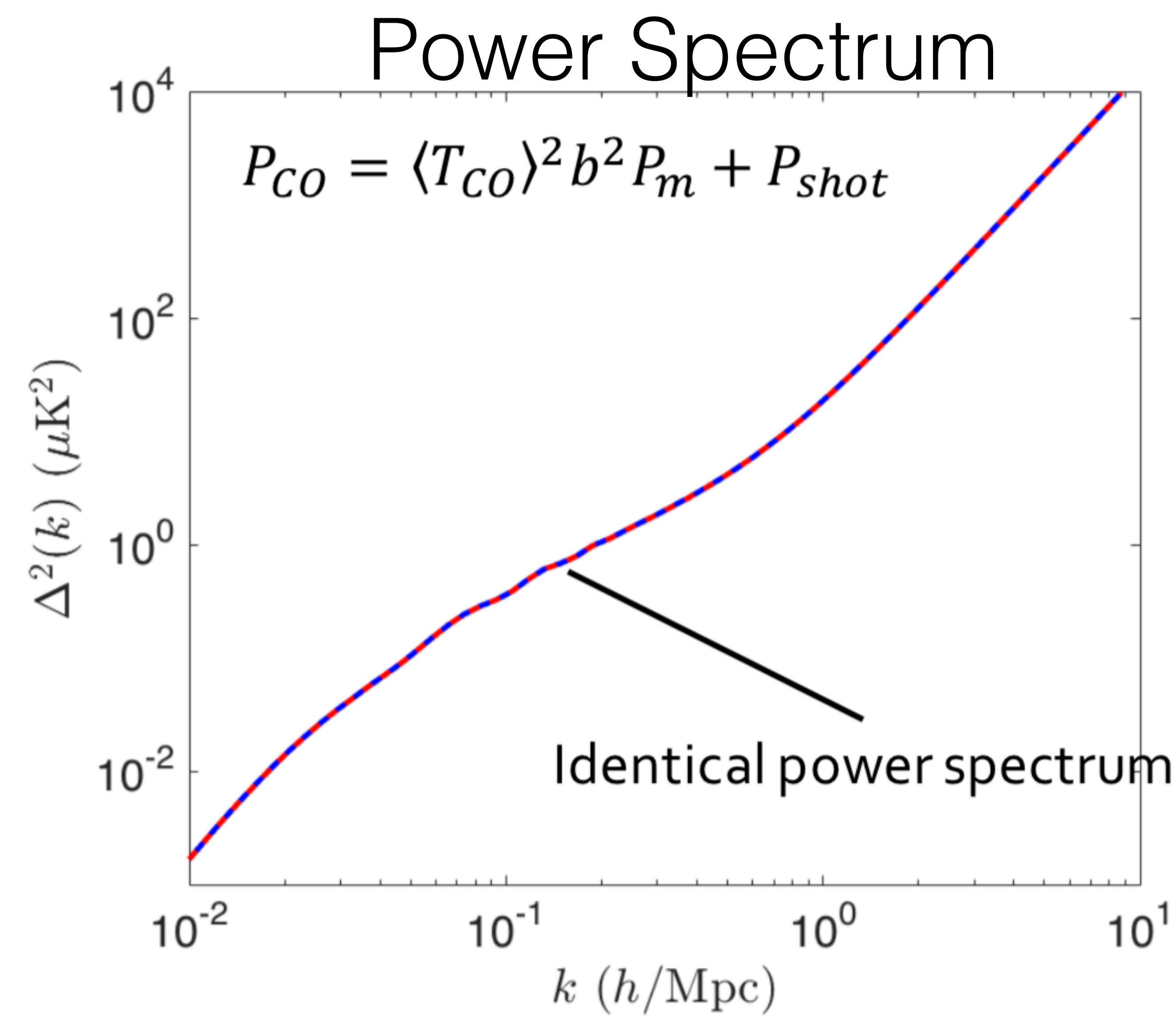
$$\Phi = \Phi^* \left(\frac{L}{L_*} \right)^{\alpha} e^{-L/L_*} dL \quad L > L_{\min}$$



Embracing Statistical Methods

- Statistically-based Measurements Map to Physical Distributions
  - e.g., P(D):



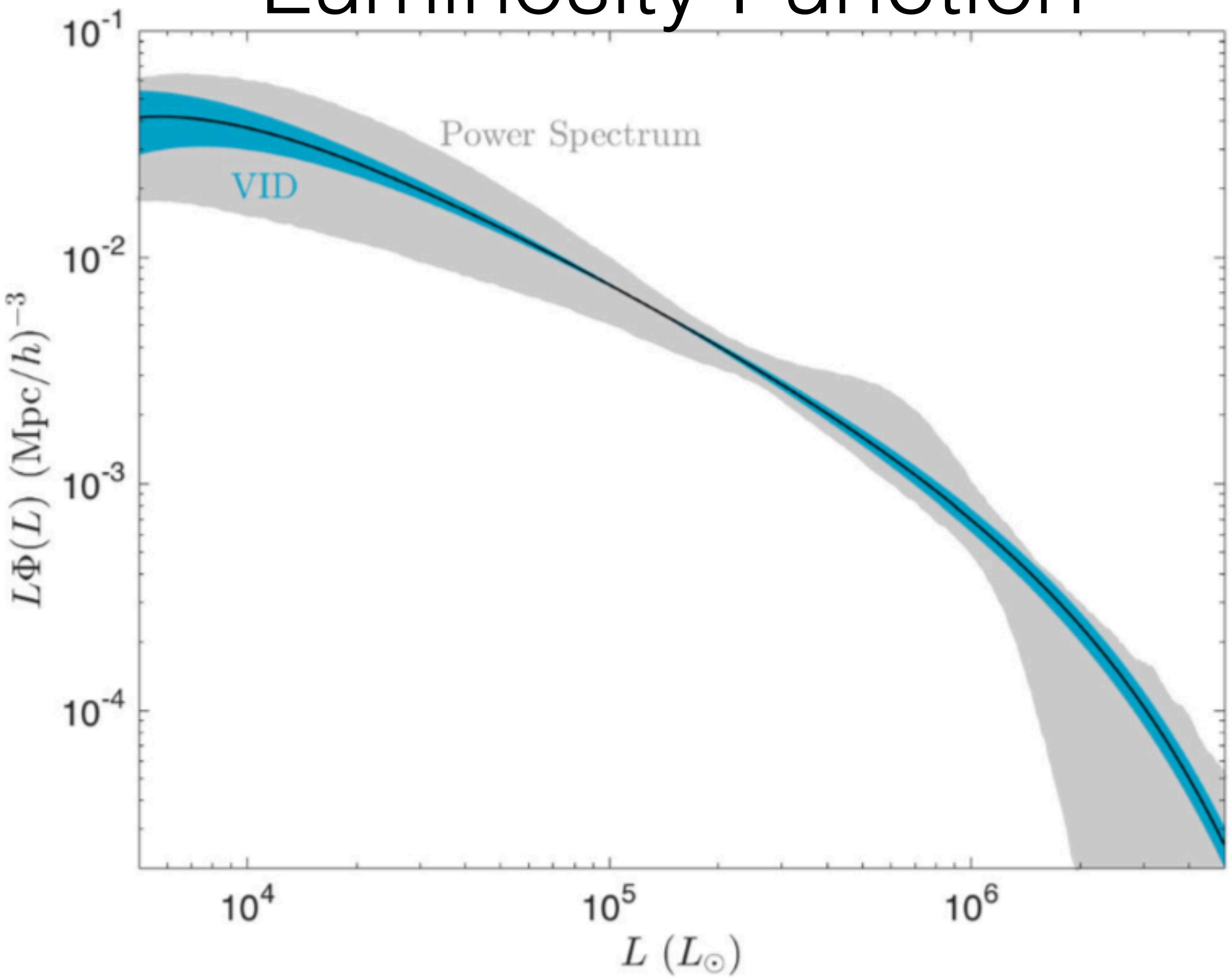


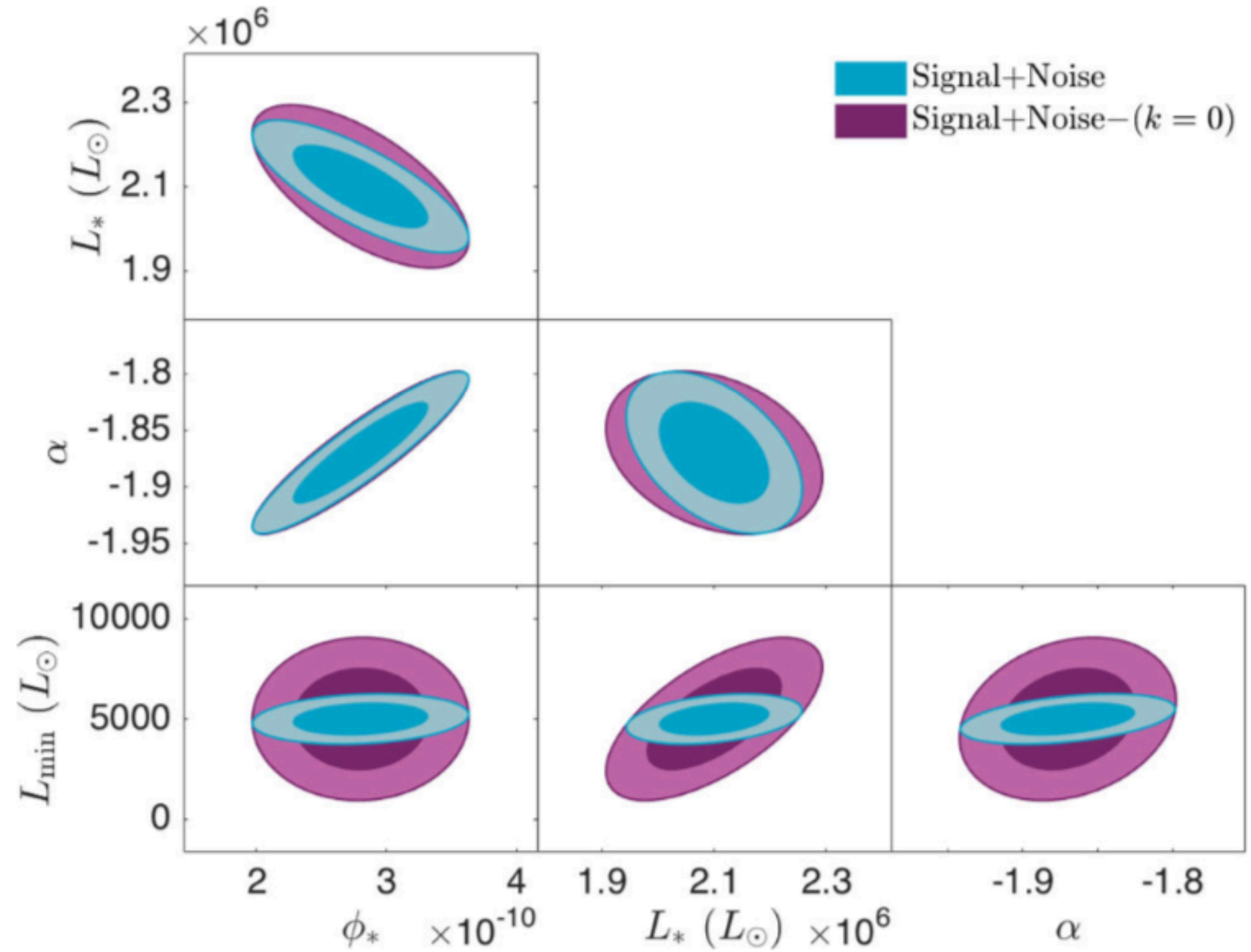
Breysse et al. 2017 — arXiv:1609.01728

Embracing Statistical Methods

- Statistically-based Measurements Map to Physical Distributions
  - e.g., P(D), also known as Voxel Intensity Distribution (VID):

Luminosity Function

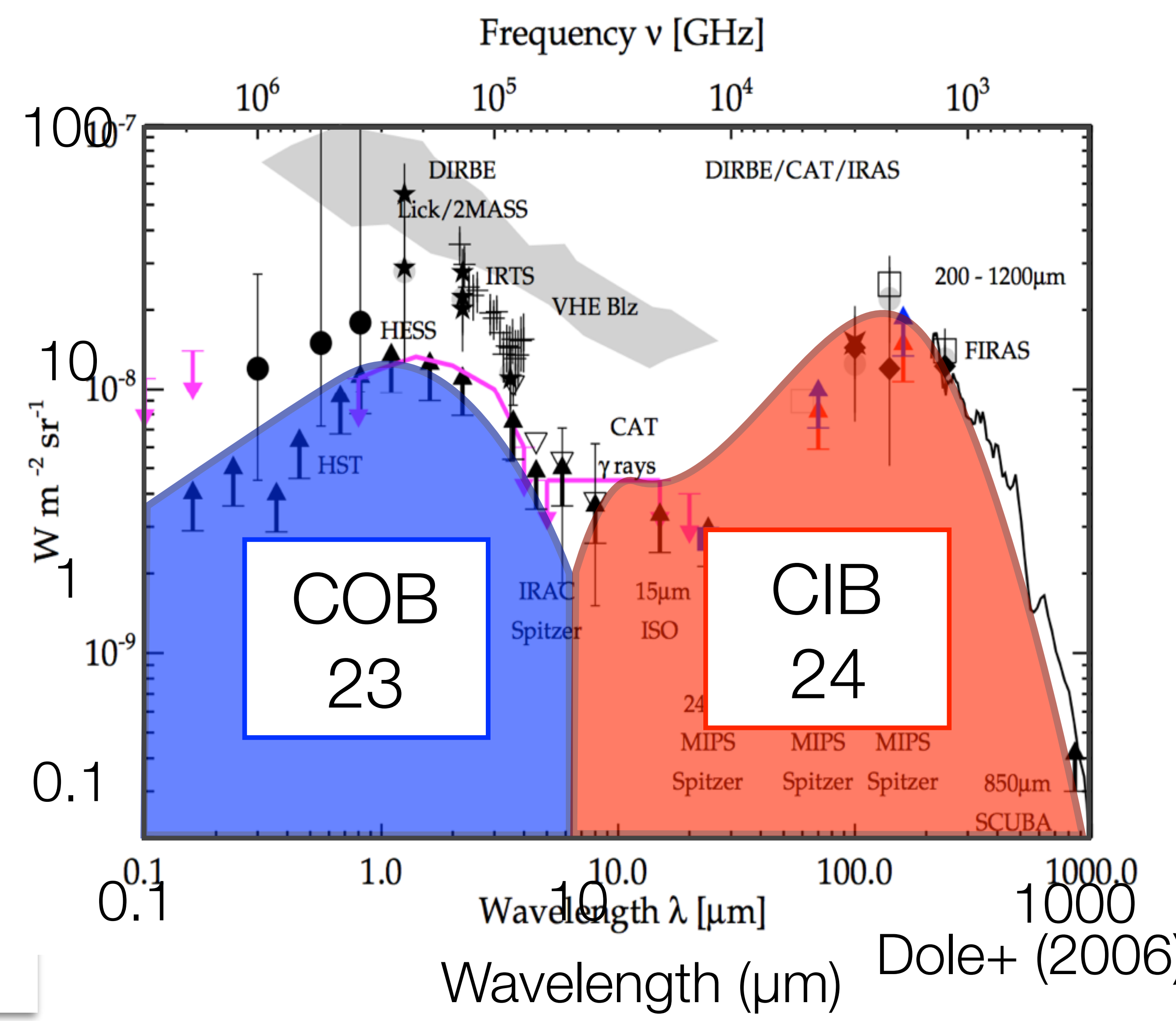




Breysse et al. 2017 — arXiv:1609.01728

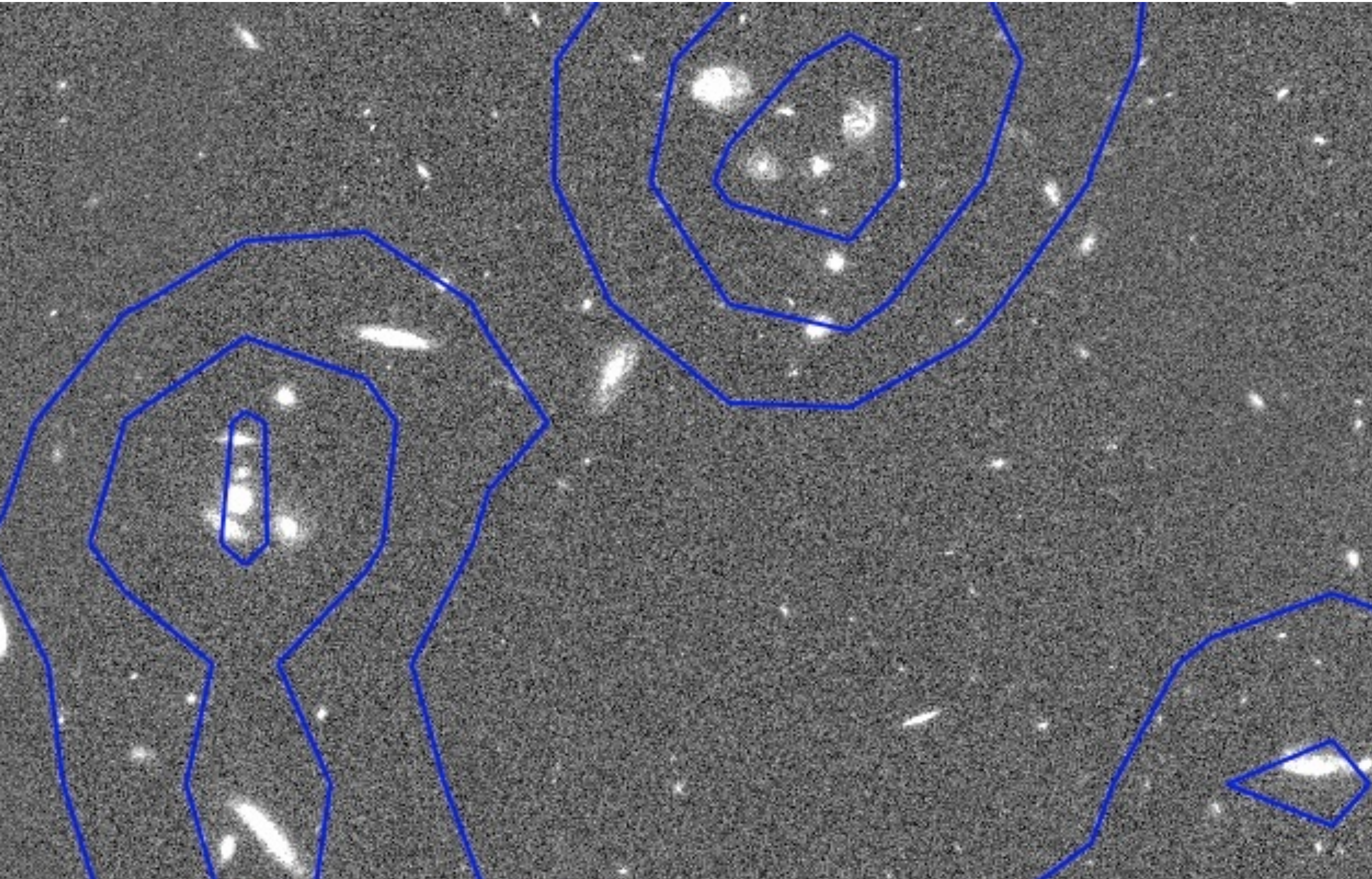
Statistical Methods & CIB: A Success Story

- CIB provides potential blueprint for line-intensity mapping.
- Keys to CIB progress:
  - ➡Technology and better data.
  - ➡Statistical Techniques.
  - ➡Modeling.



- Cosmic Infrared Background (CIB; λ = 8-1000 µm) contains energy similar to UV/Optical/Near-infrared background.

Challenge: Source Confusion



Statistical Methods & CIB: A Success Story

SPECTRUM AND ANISOTROPY OF THE COSMIC INFRARED BACKGROUND

J. R. BOND[1]
Physics Department, Stanford University; and Institute for Theoretical Physics, University of California–Santa Barbara
B. J. CARR
Institute for Theoretical Physics, University of California–Santa Barbara; Queen Mary College, London University; and Astrophysics Group, Fermilab
AND
C. J. HOGAN

- Measuring the power spectrum of the CIB was first proposed by Bond, Carr, & Hogan (1984)
- The CIB was first detected with FIRAS on COBE, in papers by Puget et al. (1998) and Fixsen et al. (1998)

Letter to the Editor

Tentative detection of a cosmic far-infrared background with COBE

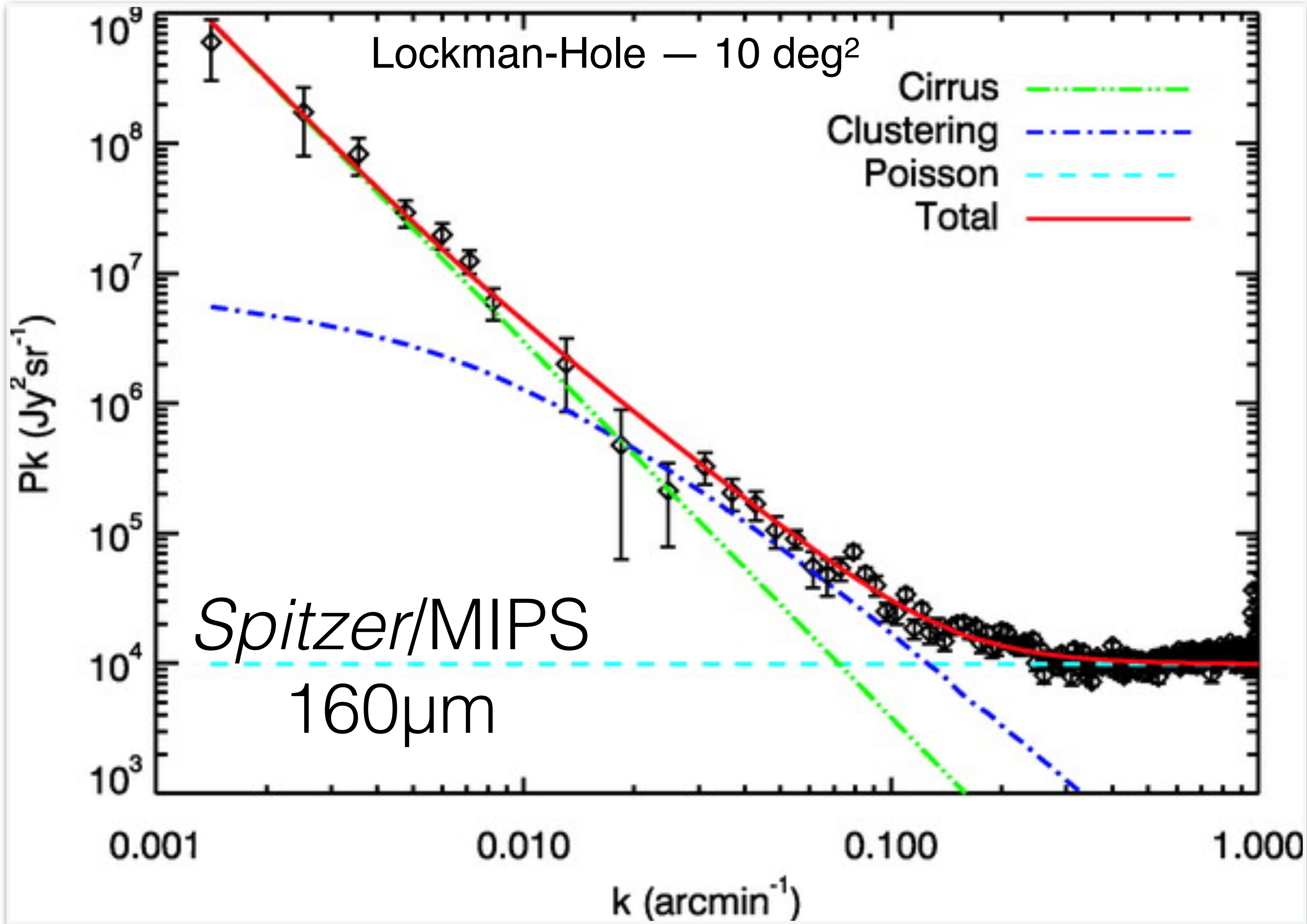
J.-L. Puget[1], A. Abergel[1], J.-P. Bernard[1], F. Boulanger[1], W.B. Burton[2], F.-X. Désert[1], and D. Hartmann[2,3]

[1] Institut d'Astrophysique Spatiale, Bât. 121, Université Paris XI, F-91405 Orsay Cedex France (puget@ias.fr)
[2] Sterrewacht Leiden, Postbox 9503, 2300 RA Leiden, The Netherlands
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

Received 4 August 1995 / Accepted 12 December 1995

Statistical Methods & CIB: A Success Story

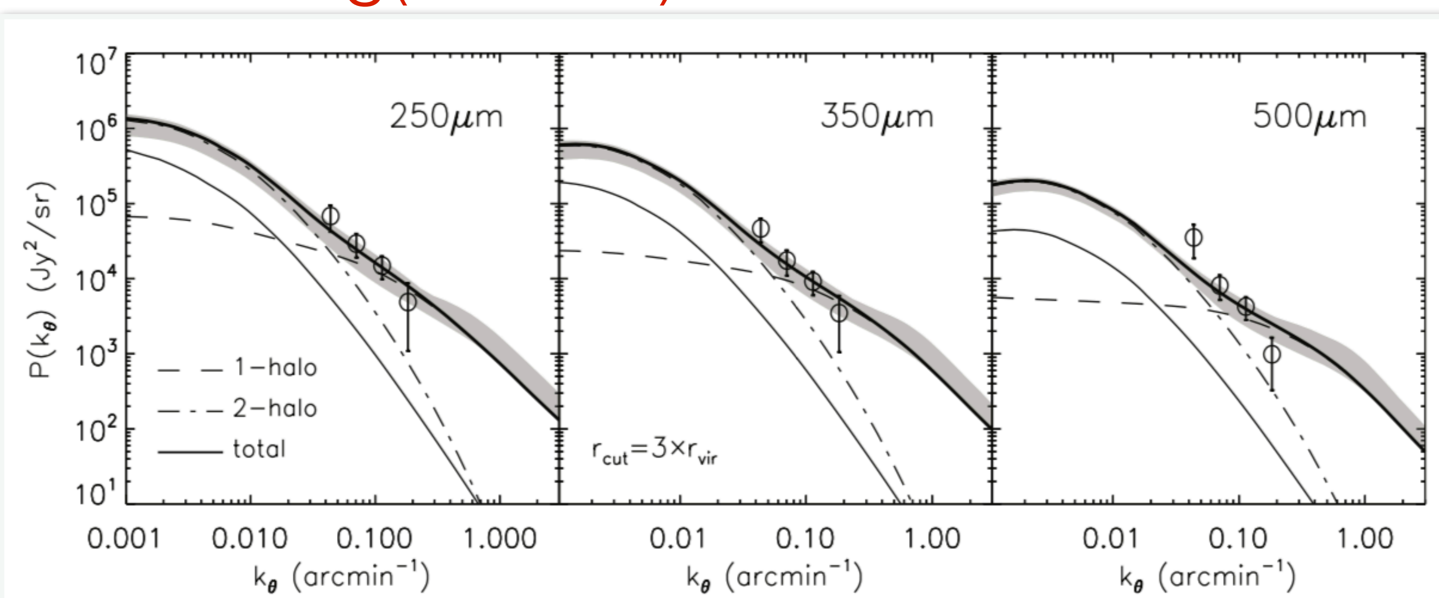
- First detection of the CIB power spectrum *Spitzer*/MIPS 160μm.
- Key Finding
  - ➡bias = 1.74+-0.16
- Galactic Cirrus dominates the low-ell signal.



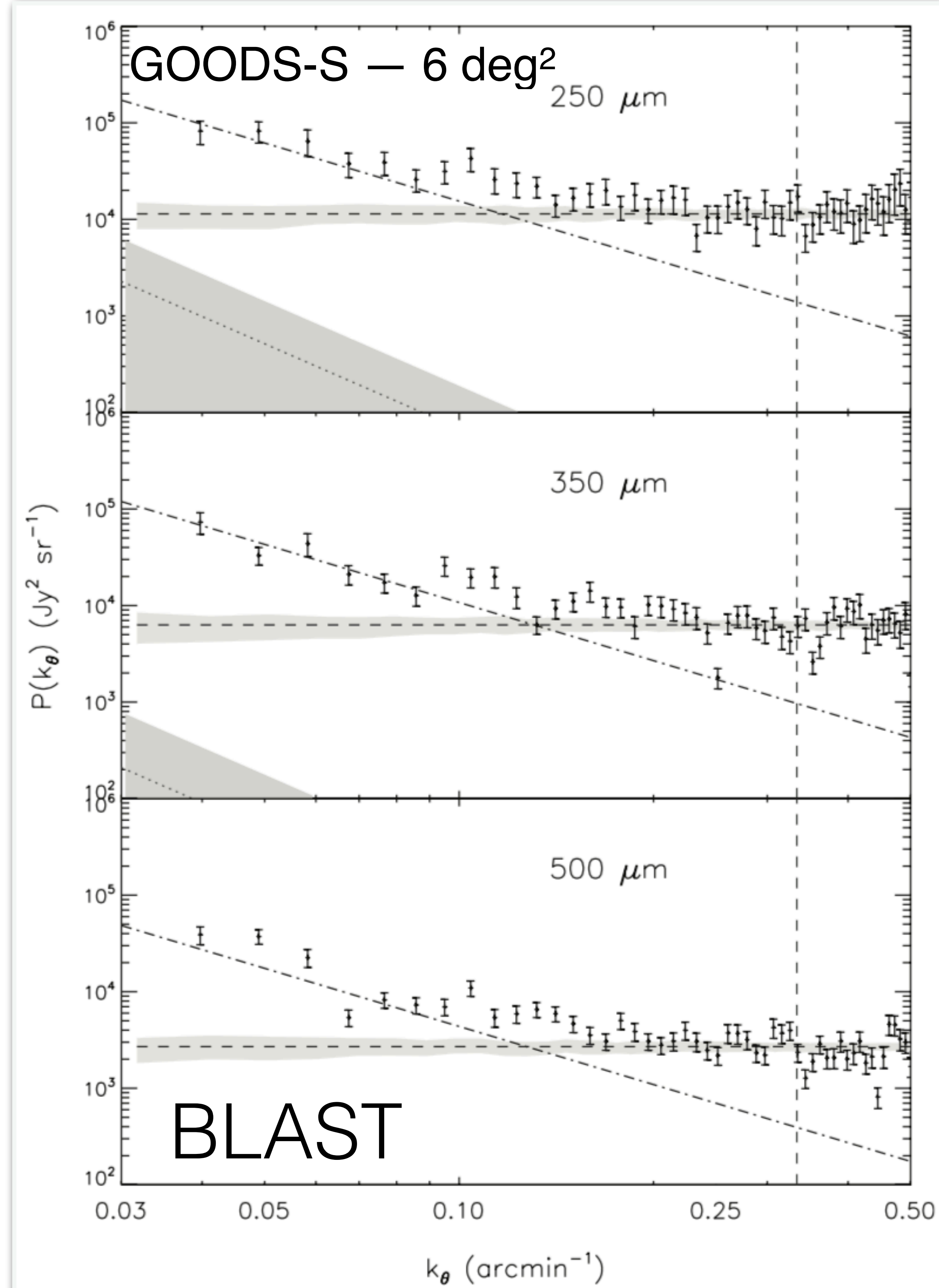
Lagache et al. (**2007**) — arXiv:0707.2443

Statistical Methods & CIB: A Success Story

- **BLAST!** — balloon-based pathfinder to SPIRE on the *Herschel Space Observatory*
- Key Findings:
  - ➡bias = 2.2-2.6
  - ➡log($M_{min}/M_{\odot}$) = 11.5
  - ➡log($M_{eff}/M_{\odot}$) = 12.8

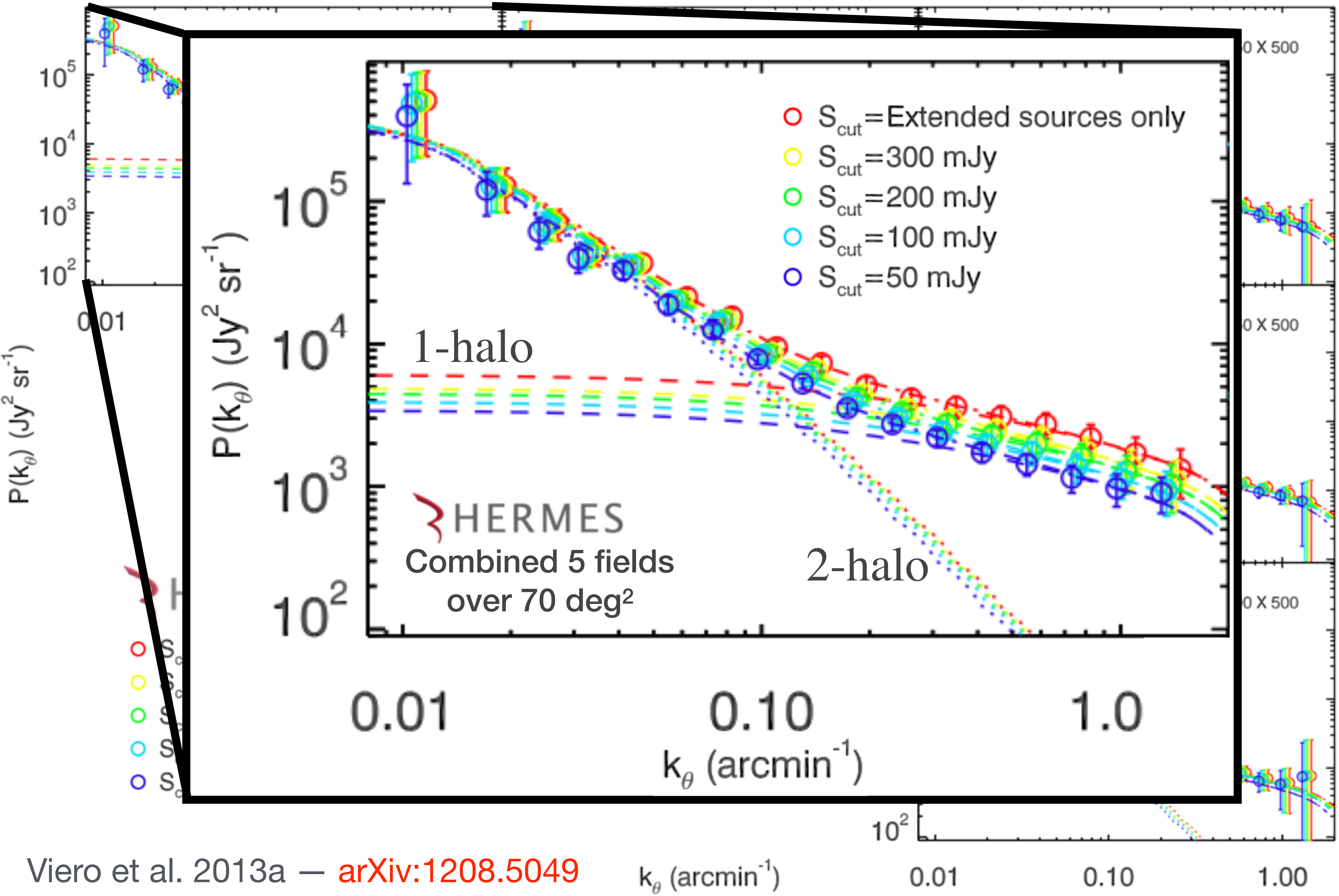


Halo Model: Mattia Negrello (Cardiff)



Viero et al. (**2009**) — arXiv:0904.1200

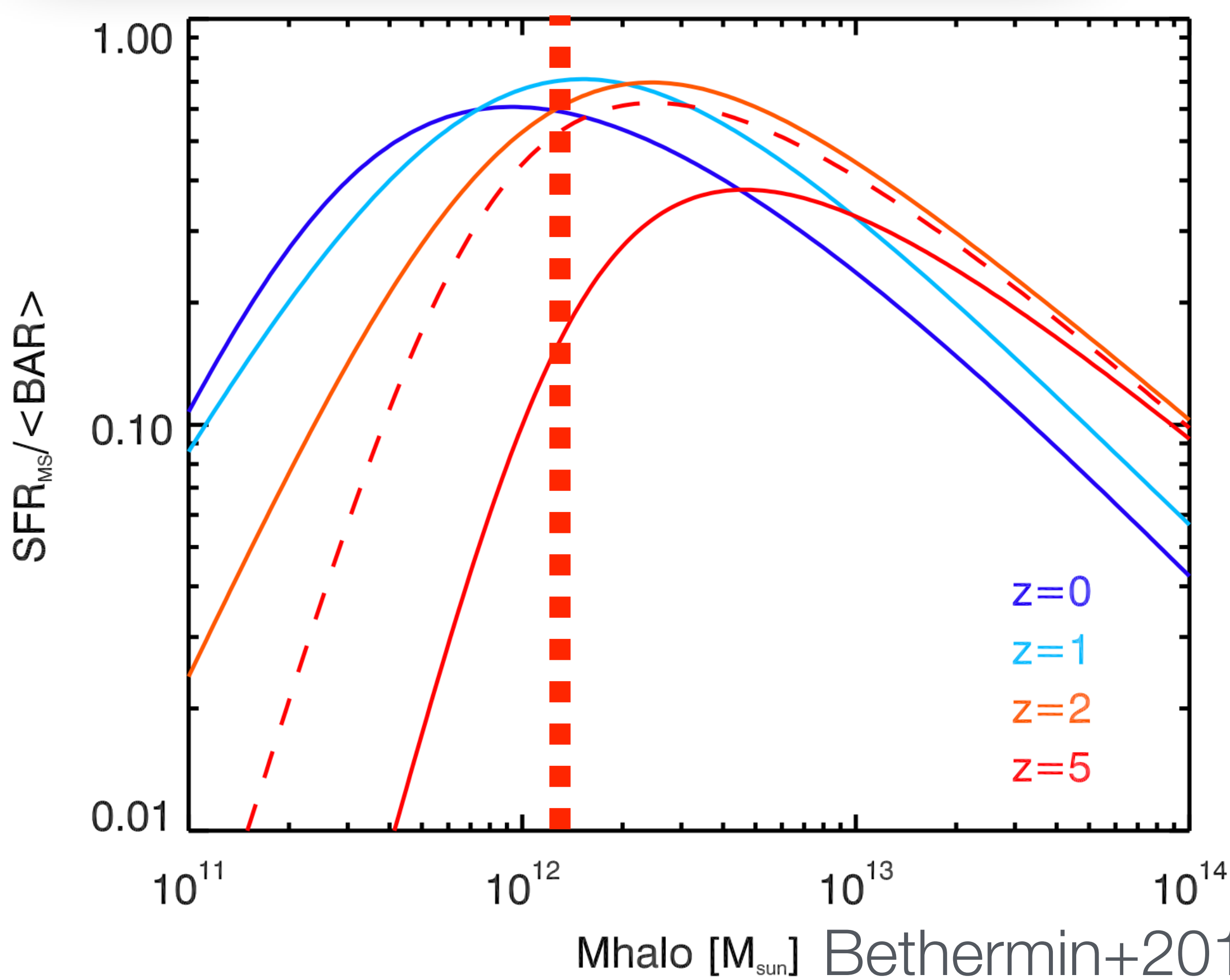
Statistical Methods & CIB: A Success Story



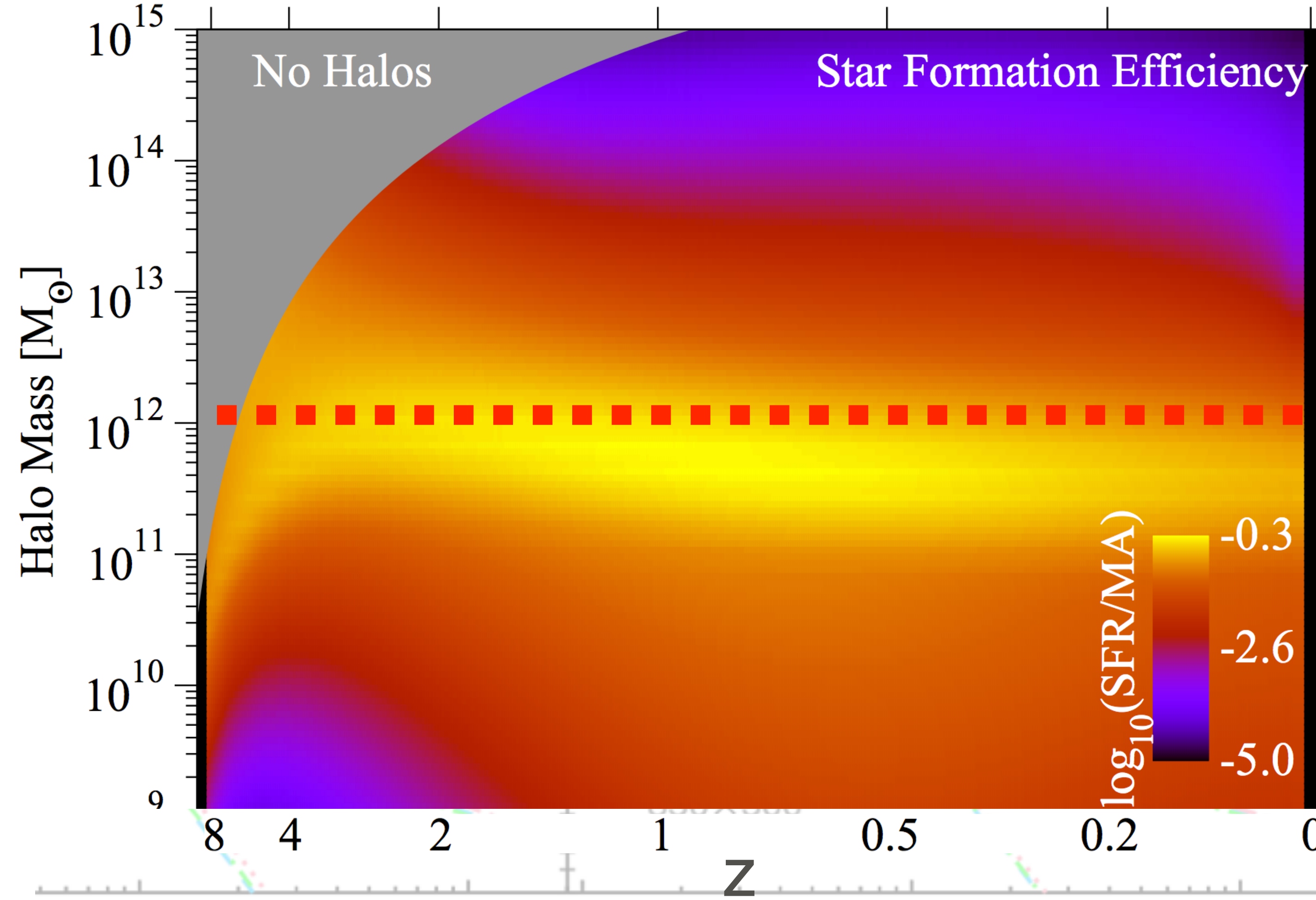
Viero et al. 2013a — arXiv:1208.5049

Statistical Methods & CIB: A Success Story

- Adopt the Shang+2012 luminosity-weighted halo model.
- Key Findings:
  - ➡ $\log(M_{min}/M_{\odot}) = 10.1 \pm 0.6$
  - ➡ $\log(M_{eff}/M_{\odot}) = 12.1 \pm 0.5$



Bethermin+2013

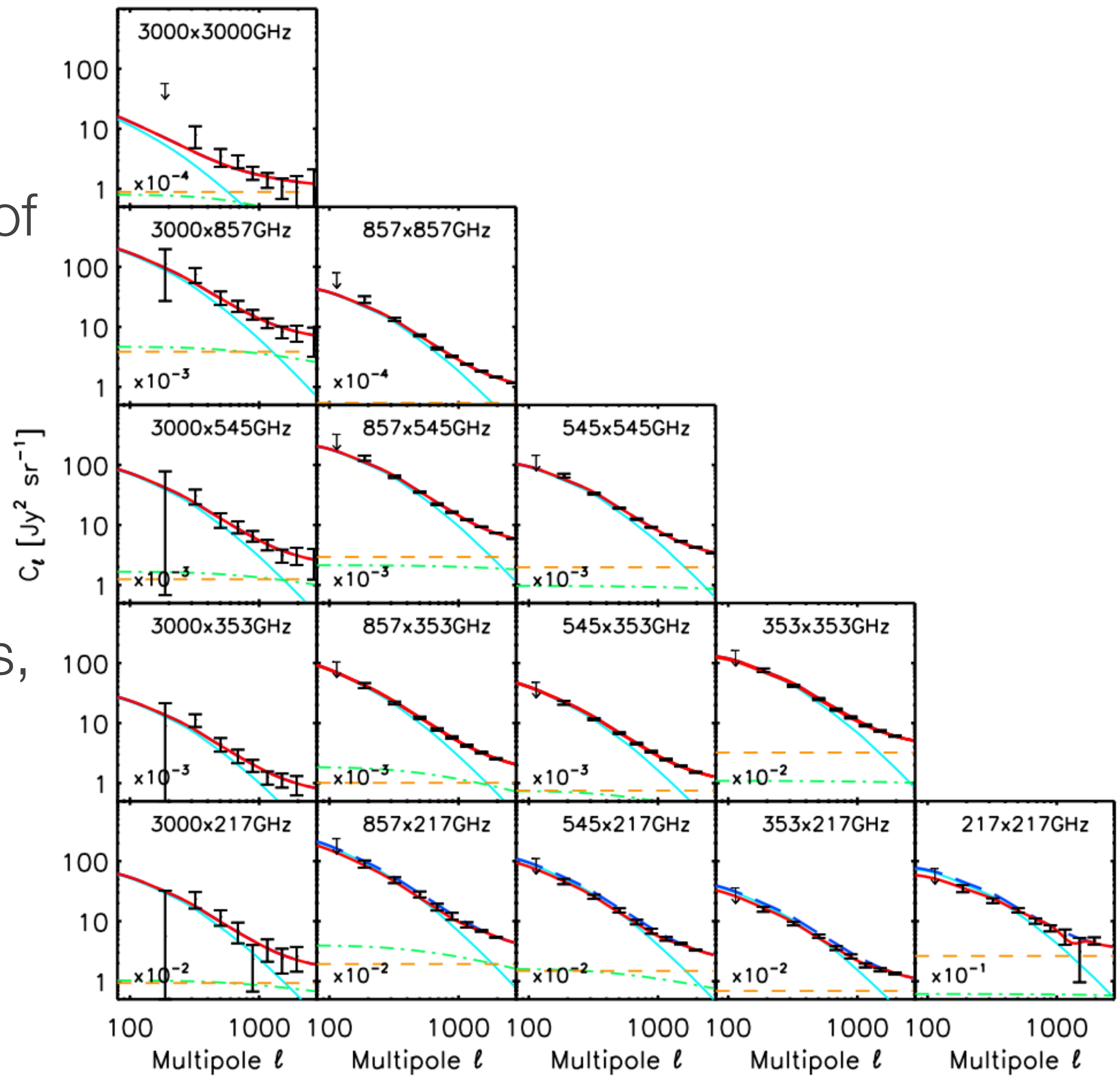


Behroozi+2013

Halo Model: Lingyu Wang (Groningen)

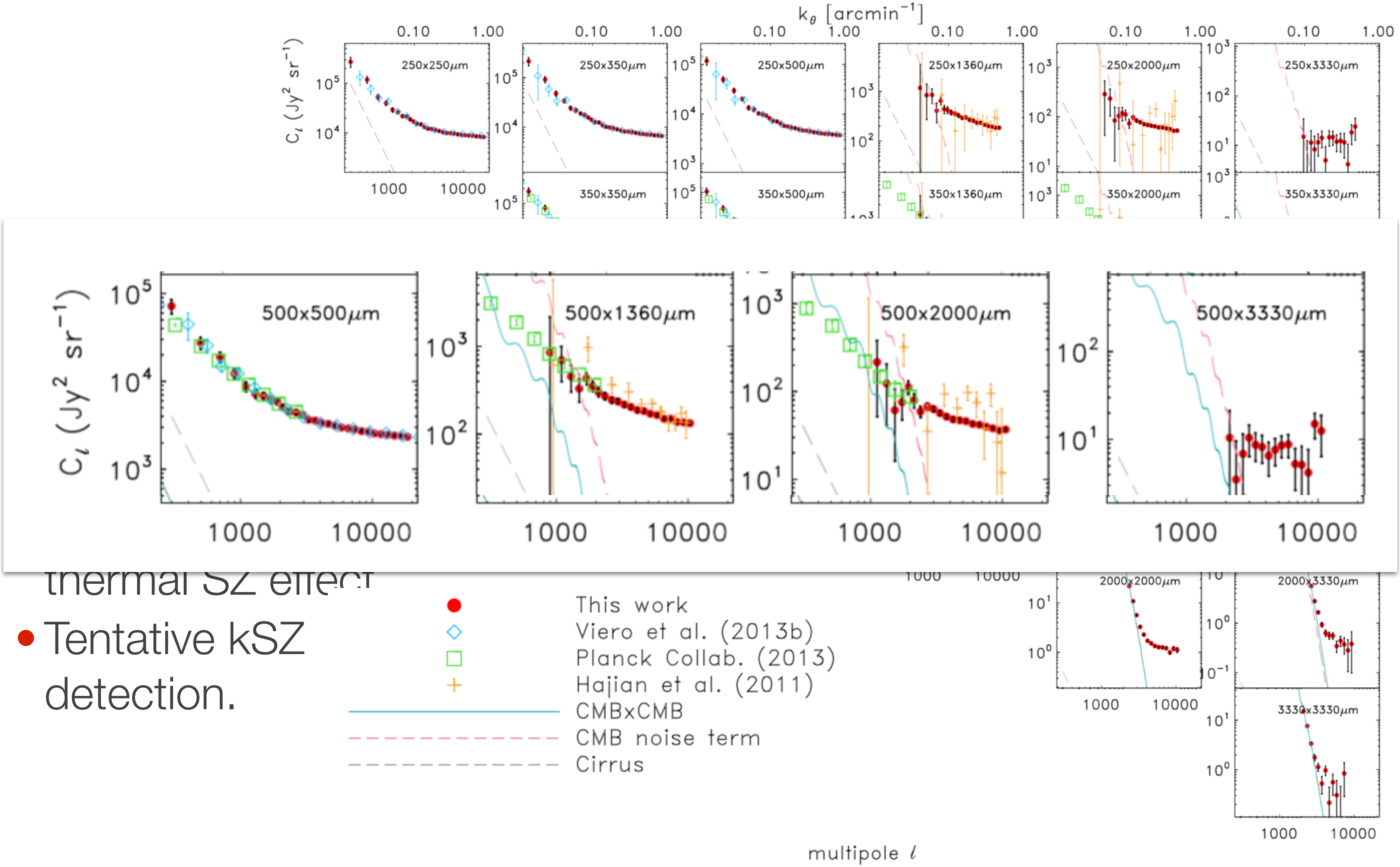
Statistical Methods & CIB: A Success Story

- Cross-Frequency includes 100um (IRAS)
- Also adopt halo model of Shang+(2012)
- Key Findings:
  - ➡ $\log(M_{eff}/M_{\odot}) = 12.6$
  - ➡ first measurement of the bi-spectrum
- Sensitive to large-scales, but find Poisson and 1-halo term degenerate.
  - ➡ Poisson levels high
  - ➡ Mak et al. 2017 find values closer to Viero et al. 2013



Planck Collaboration XXX (**2013**) — arXiv:1309.0382

Statistical Methods & CIB: A Success Story

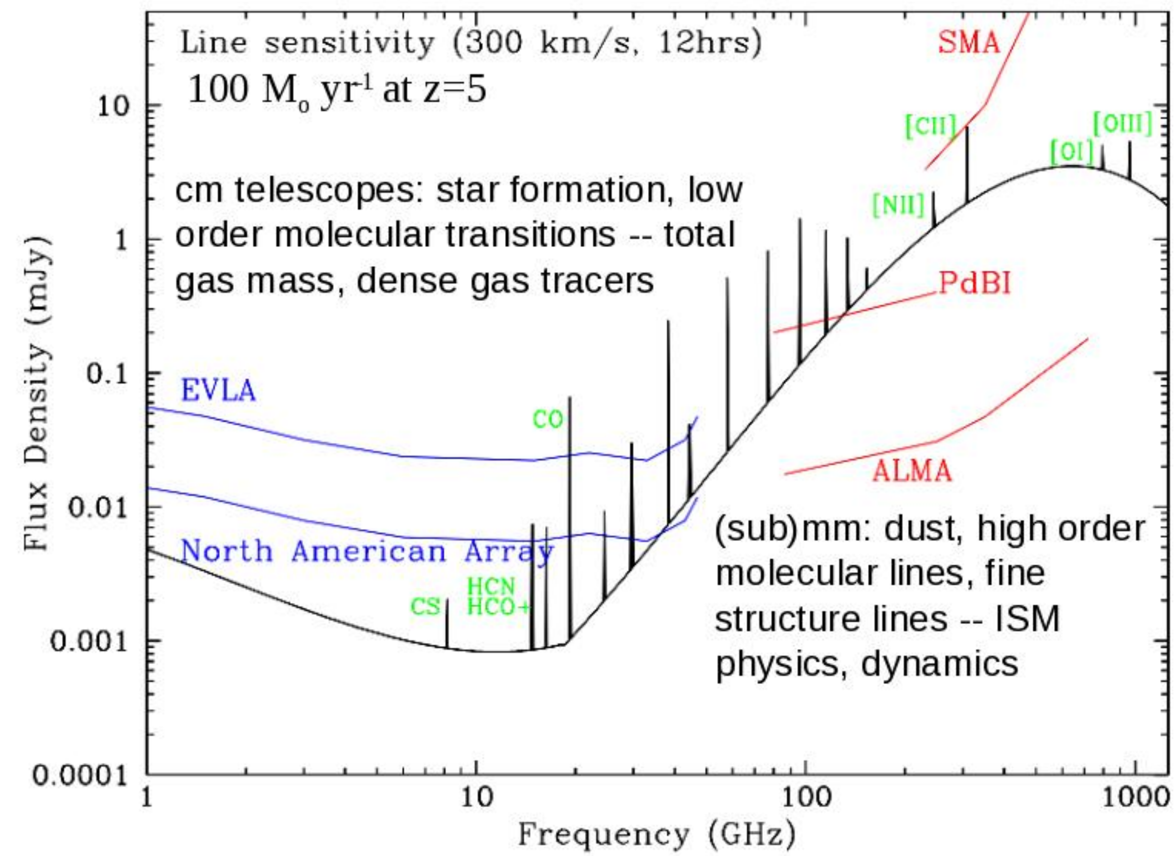


- Tentative kSZ detection.

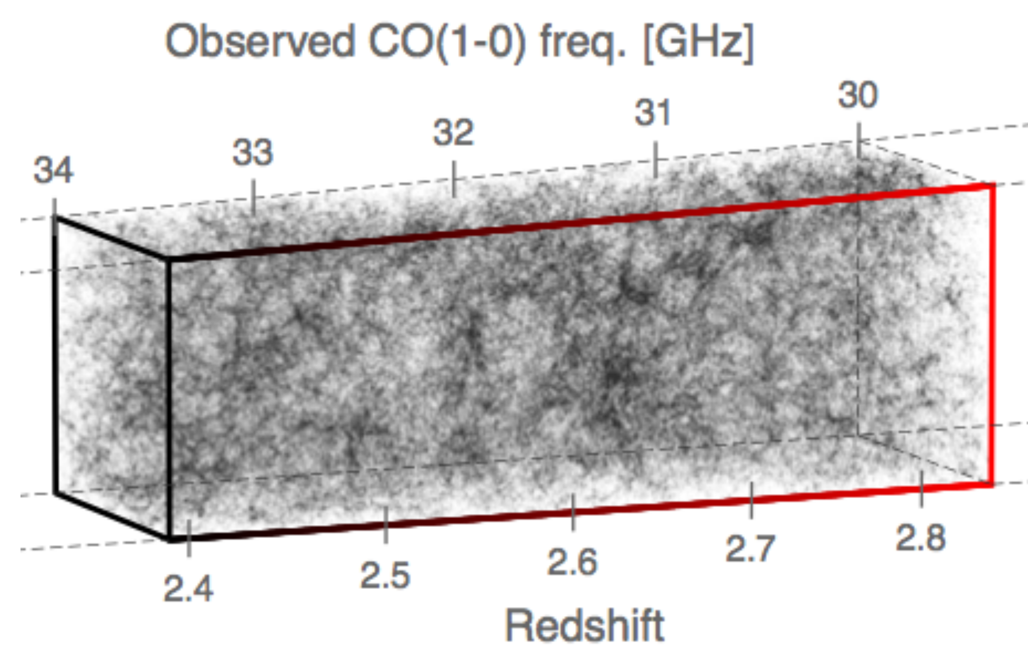
Viero et al. (**2018, in prep.)**

2D (Continuum-) to 3D (Line-) Intensity Mapping

- Rapid progress in CIB was made possible through combination of:
  - ➡New technology and better data.
  - ➡Statistical Techniques.
  - ➡Modeling.
- Limitations of the CIB thus far include:
  - ➡2D — no redshift information.
  - ➡Tells us about dust but not about gas.
- Opening up the z-direction (frequency) will allow us to extend the technique to 3D, exploiting fine-structure lines in the galaxy SED.



Carilli et al. (2010) — arXiv:1006.0988

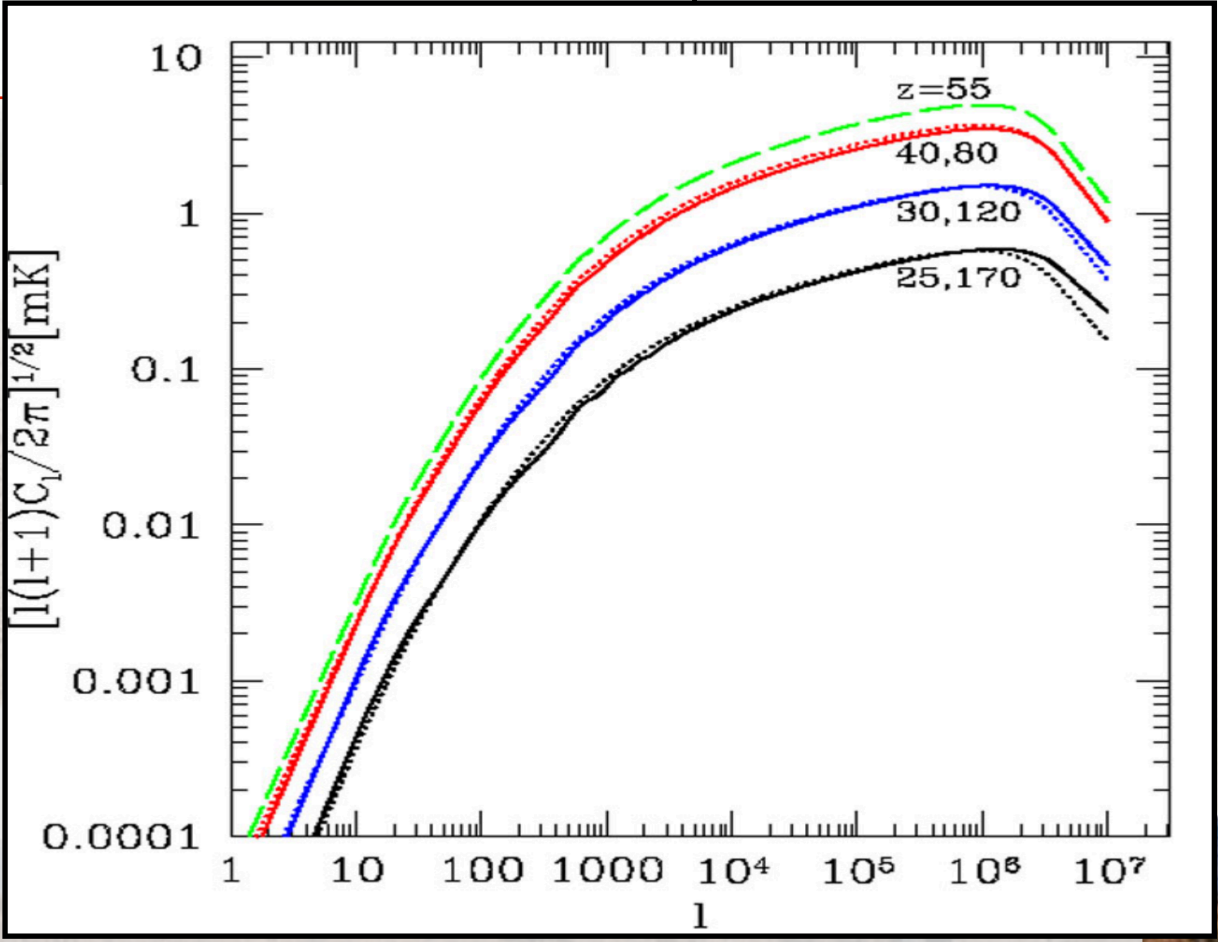


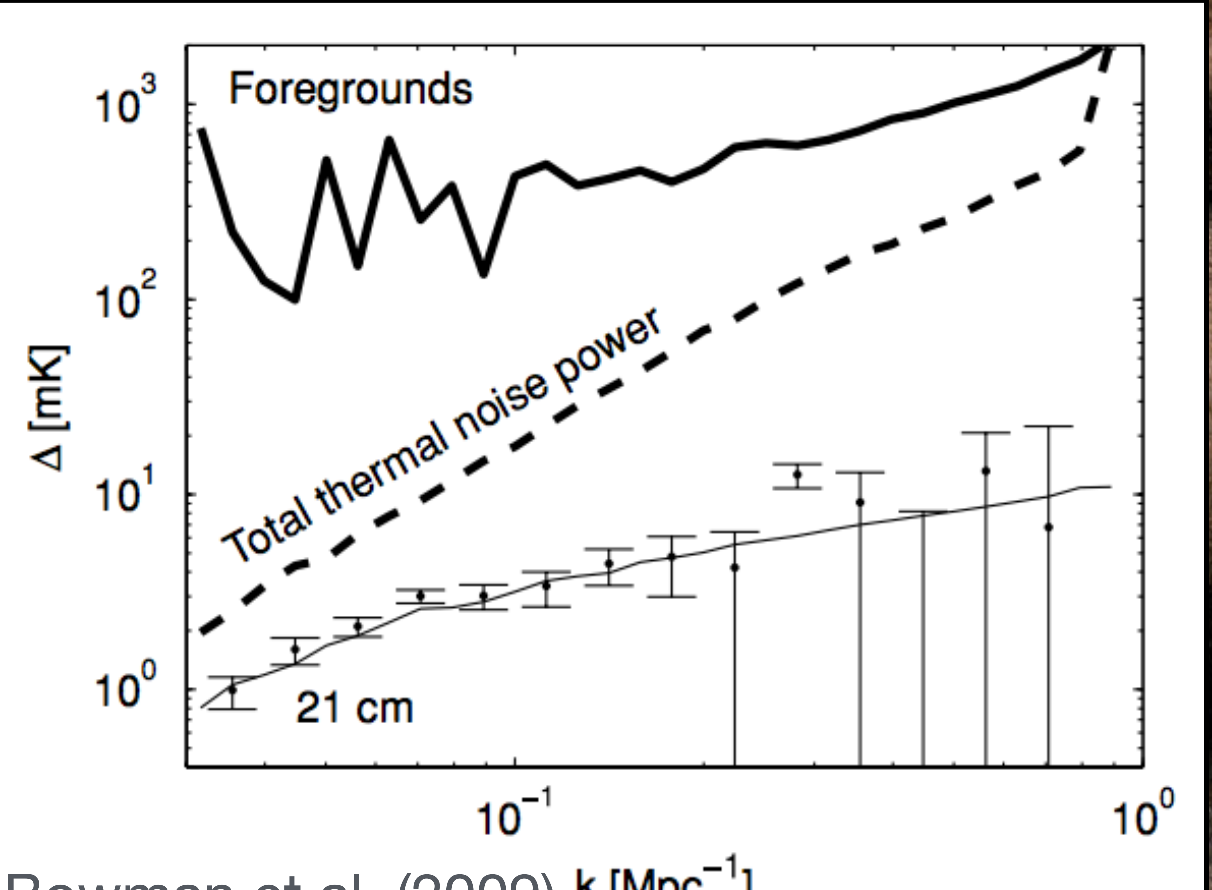
Li et al. (2016) — arXiv:1503.08833

HI Intensity Mapping

- Neutral Hydrogen, HI, is incredibly abundant (90% of all atoms!), emits at 21cm, and traces the evolution of the IGM during EoR, making it a perfect candidate line for IM.
- Instruments underway include:
  - ➡Square Kilometer Array (SKA)
  - ➡Hydrogen EoR Array (HERA)
  - ➡Precision Array for Probing Epoch of Reionization (PAPER)
  - ➡Murchison Widefield Array (MWA)
- But noise/foregrounds swap signal
  - ➡Smooth in frequency, but must be extremely well characterized!

EoR Power Spectrum





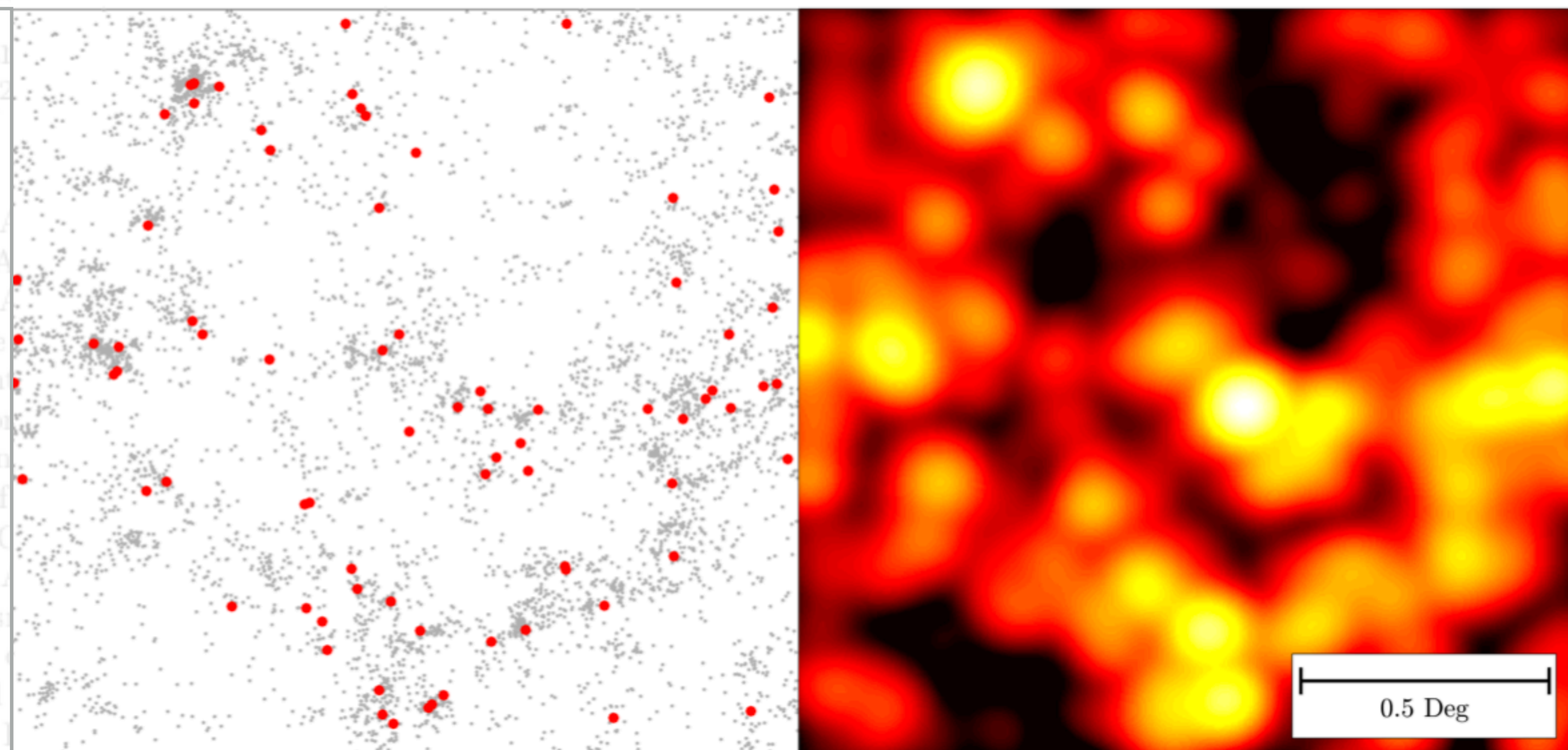
Bowman et al. (2009)

Line-Intensity Mapping

- **Line-Intensity Mapping** borrows the principle idea from HI intensity mapping, but instead observes the collected emission from ***Galaxies.***
- Efficient! Small telescopes, shorter integrations.
- Multiple line candidates (CO, CII, Lya) probe different physics.

2.5 deg² field

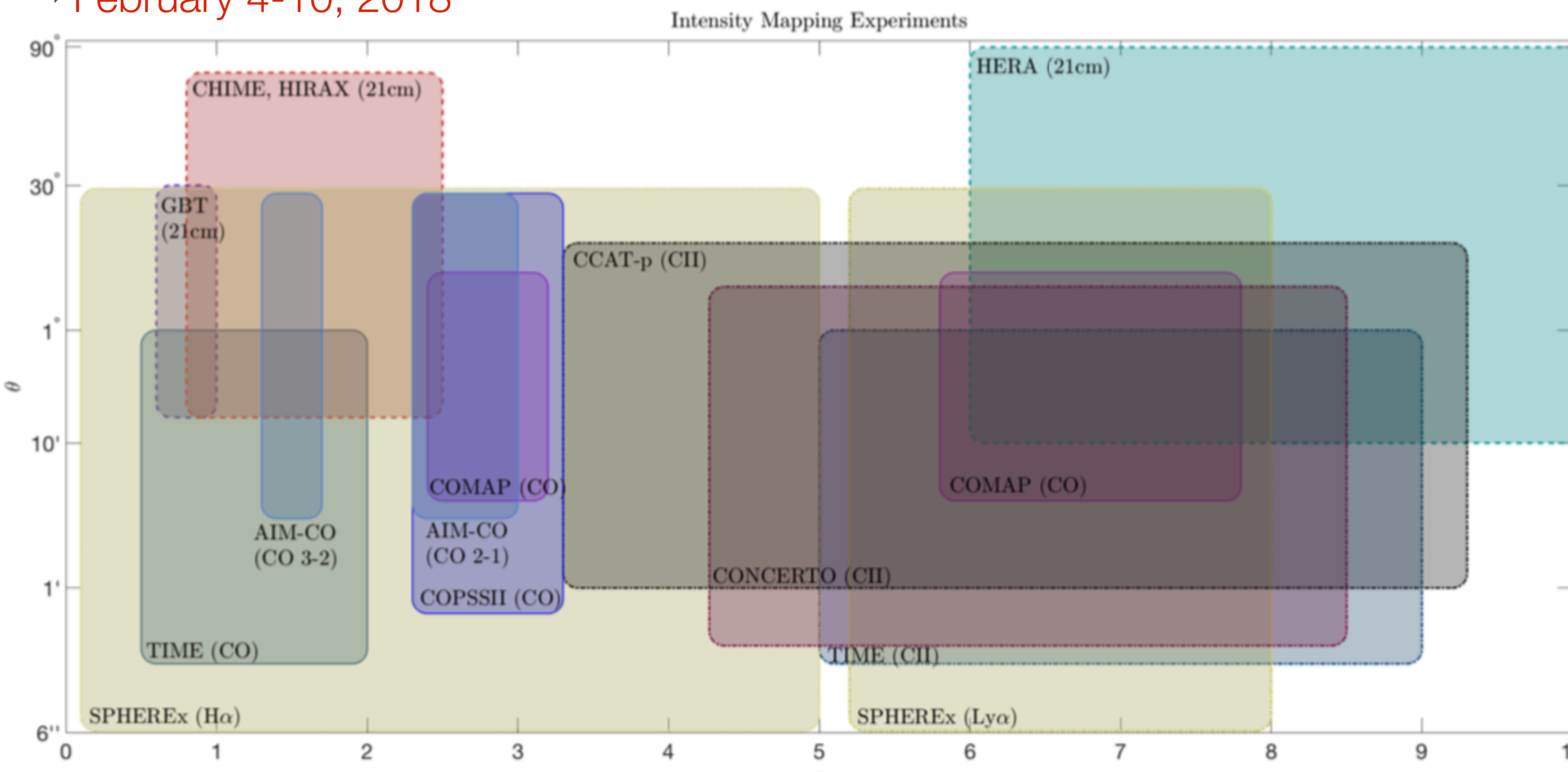
- VLA (left)
  - 27 dishes
  - 4500 hours
  - 1% sources
- COMAP (right)
  - 1 dish
  - 1500 hours



From the Line-Intensity Mapping Status Report (Kovetz, Viero et al. 2017 — arXiv:1709.09066)

Line-Intensity Mapping

- Opportunities and Challenges in Intensity Mapping
  - ➡ March 21-23, 2016, SLAC/Stanford
- Second Annual Intensity Mapping Workshop
  - ➡ June 12-14, 2017, Johns Hopkins University
- Cosmological Signals from Cosmic Dawn to the Present
  - ➡ February 4-10, 2018

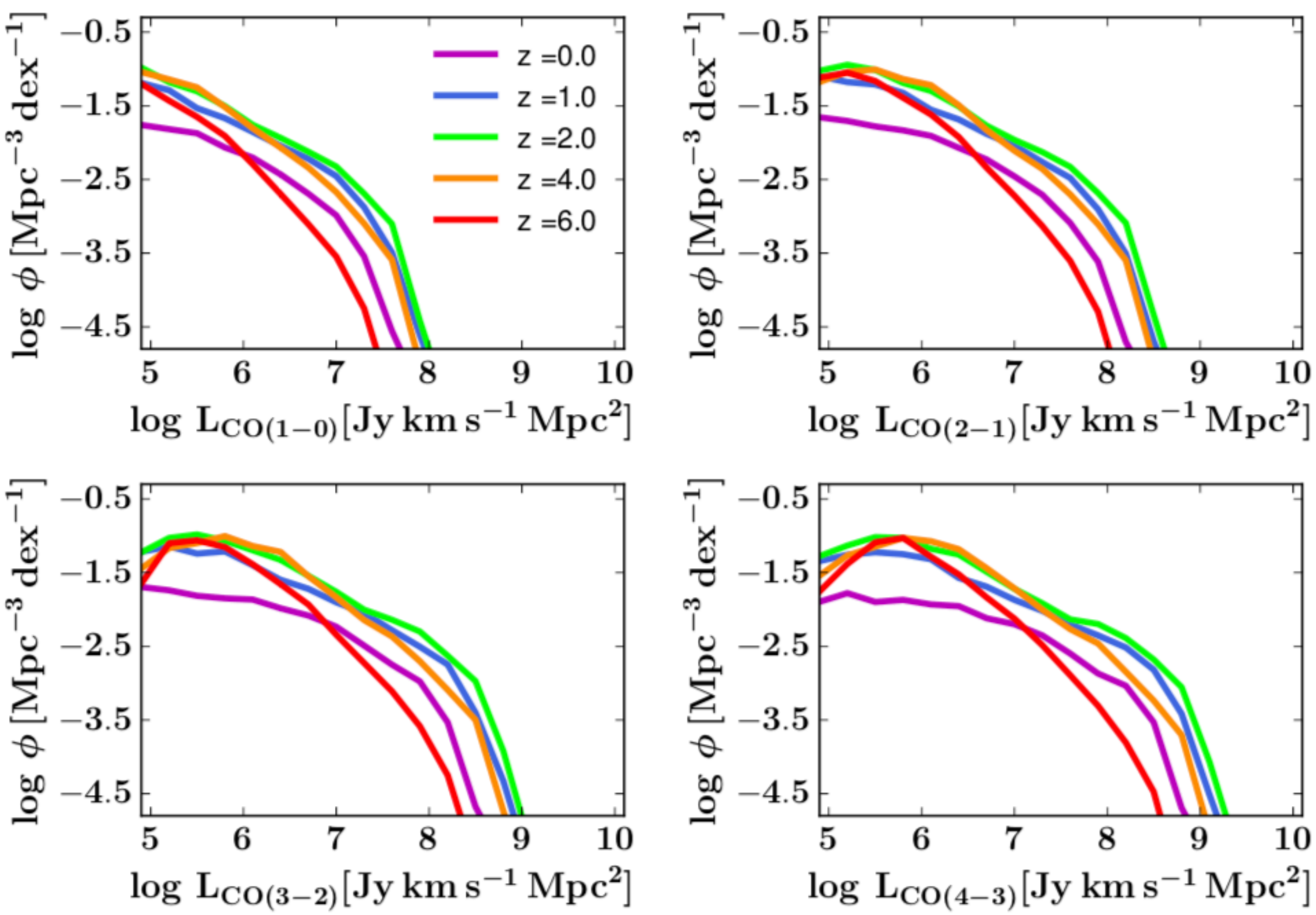


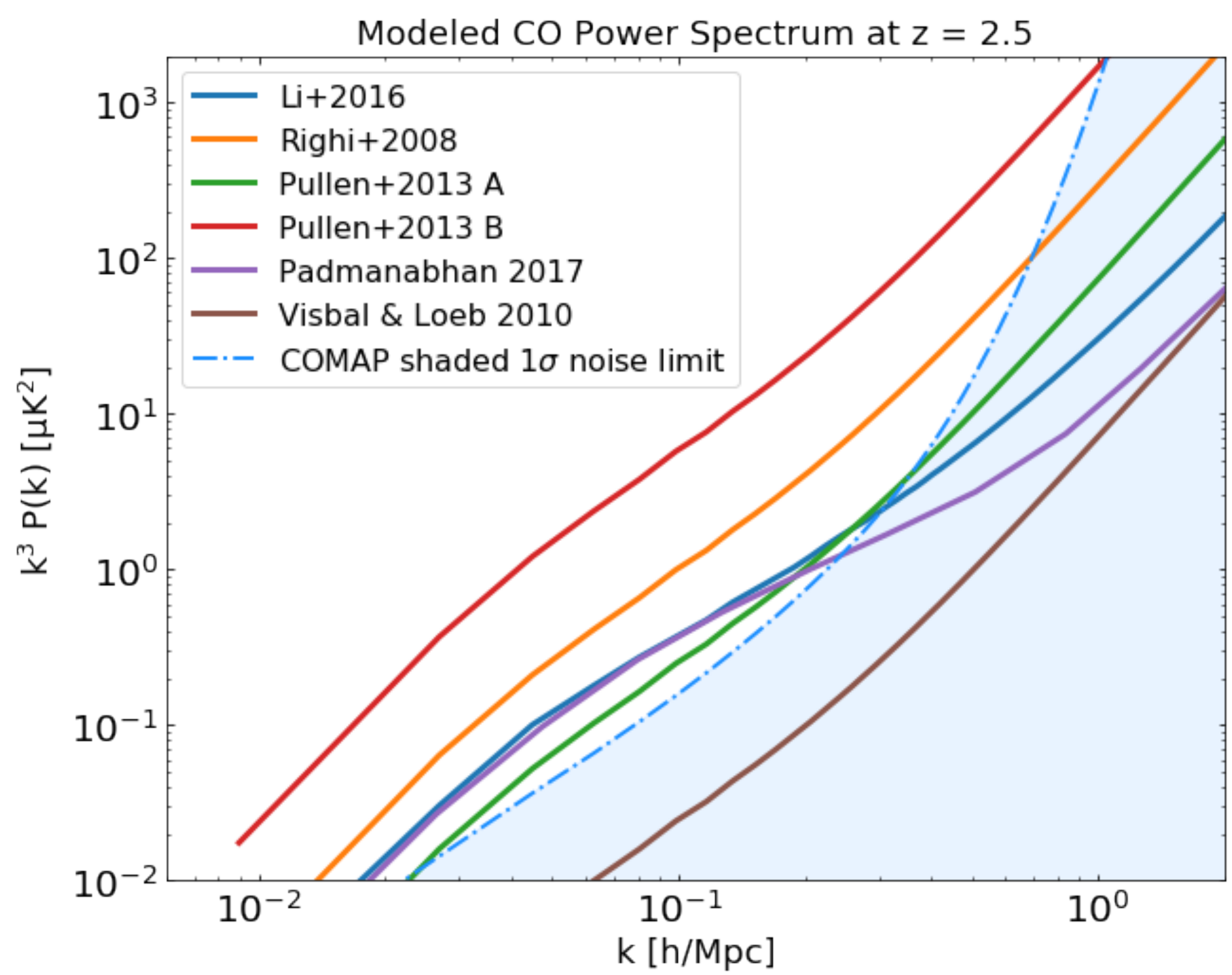
Kovetz and Breysse for the Line-Intensity Mapping Status Report — arXiv:1709.09066

Line-Intensity Mapping — CO

- CO next most abundant molecule after H_2.
- Traces star formation.
- Emission arrises from "ladder" of transitions $\nu_{1\to0}$ = 115.27 GHz. Leads to unambiguous redshift determination.

CO Luminosity Functions

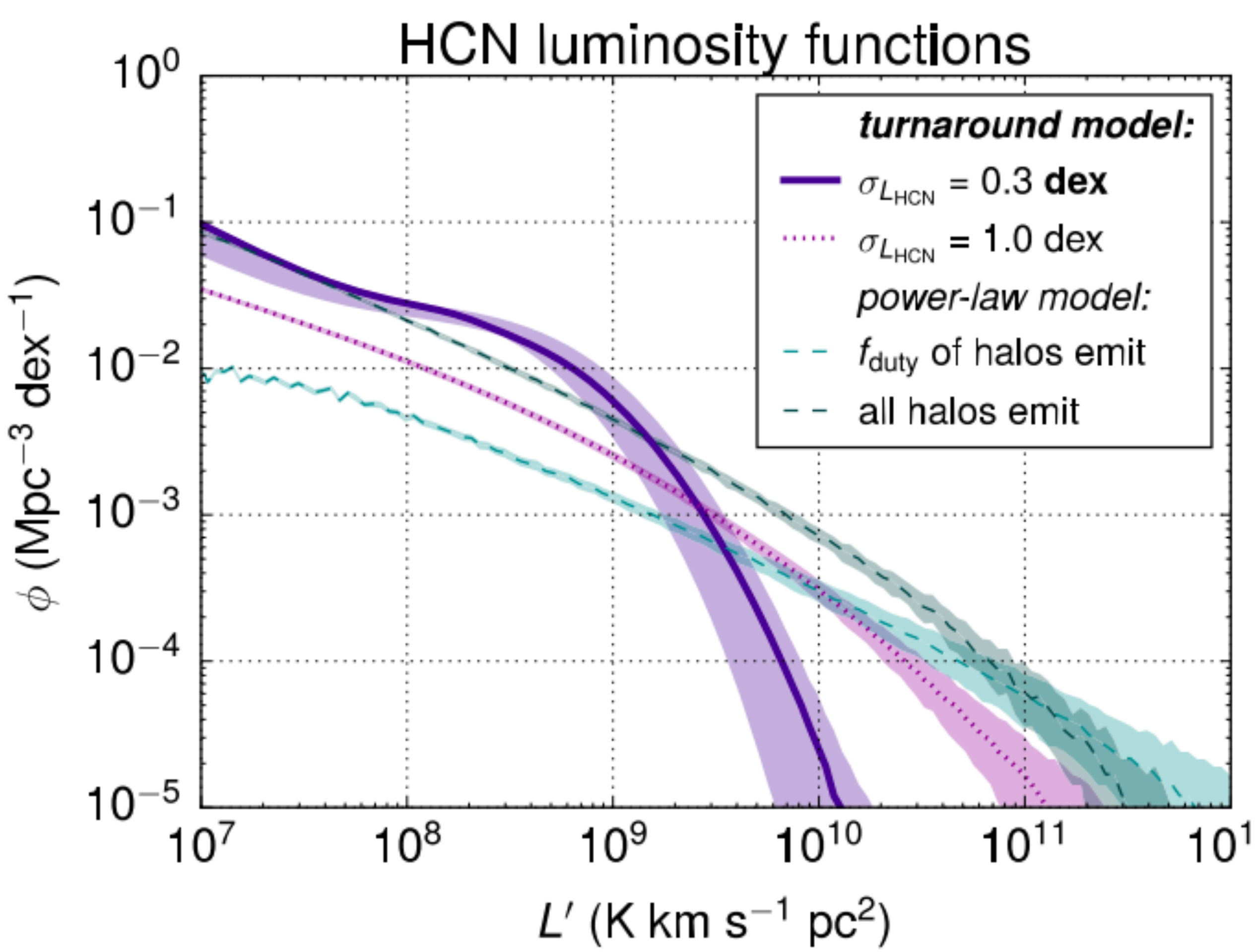


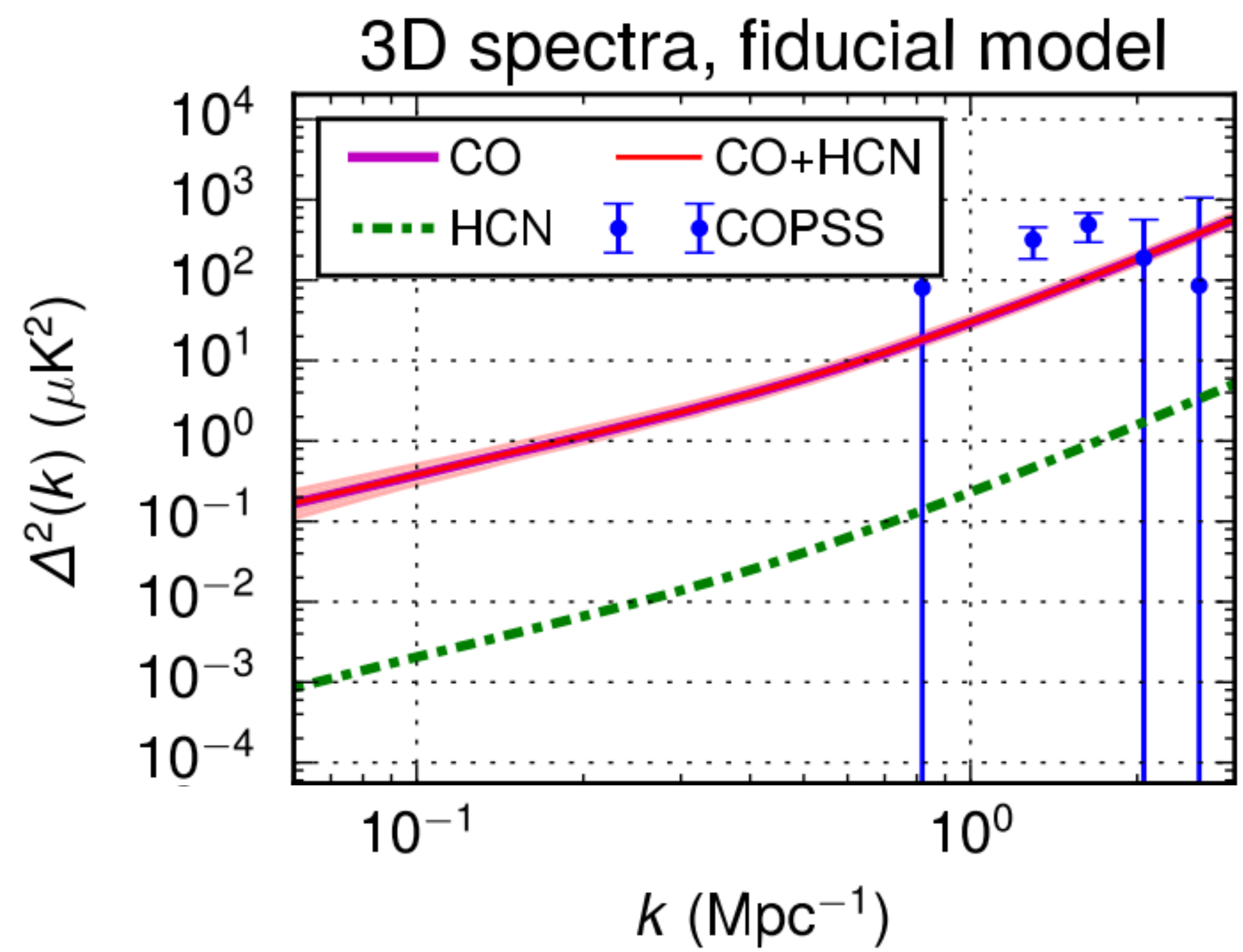


Popping+2016 for the Line-Intensity Mapping Status Report — arXiv:1709.09066

CO Foregrounds — HCN

- HCN was previously suggested to be a problem foreground.
- Chung+2017 showed that the high Poisson levels were the result of unrealistic assumptions* about the shape of the luminosity function: i.e., assuming an unbroken power-law.



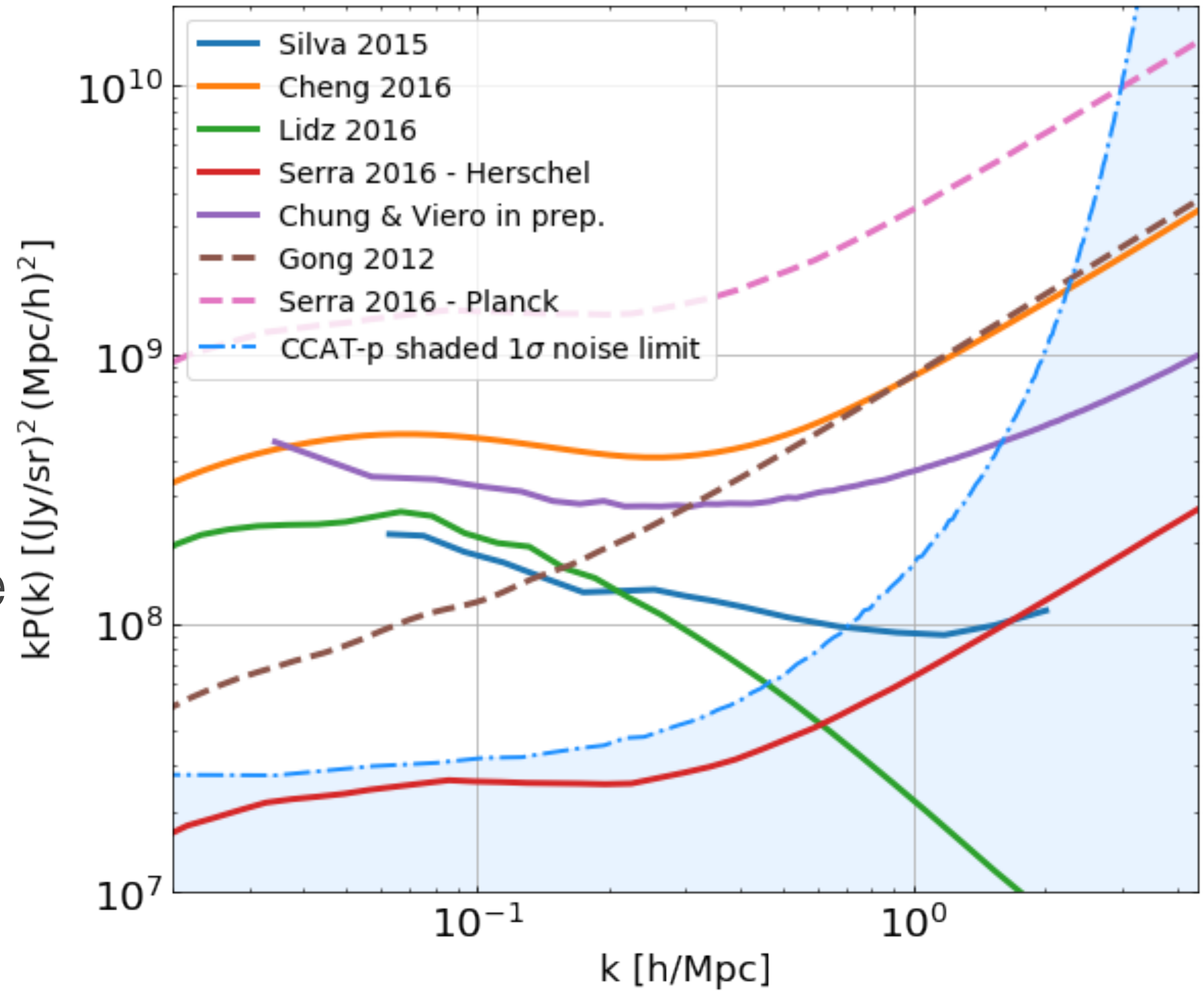


Chung, Viero et al. 2017
arXiv:1706.03005

* by now I hope you've noticed a theme!

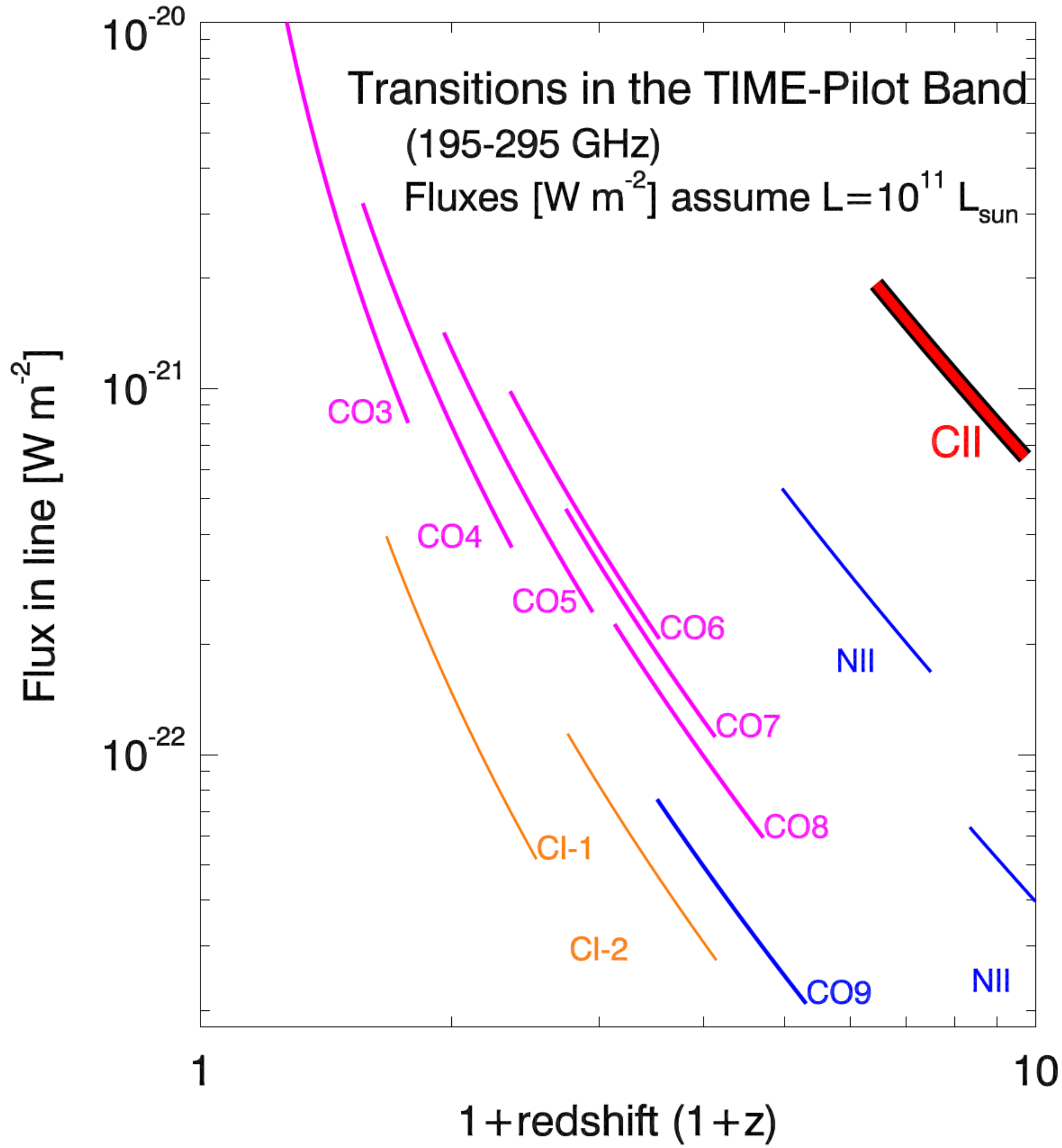
Line-Intensity Mapping — [CII]

- [CII] — singly ionized carbon fine-structure line (157.7μm)
- Makes up as much as 1% of bolometric infrared luminosity.
- Low ionization energy, is a major coolant of the ISM and tracer of star formation.
- EoR redshifts into the submm/mm.



CO Foreground Cleaning

- Targeting CII at z = 6-10 means separating signal from lower-z CO.
- In deep fields (e.g., COSMOS, UDS, GOODS), all potentially significant CO emitters (z=1-3) will be cataloged in the UV, optical, and NIR with great detail.
  - ➡ In these cases, estimators for CO can be constructed from optical predictors of the mean LIR.
  - ➡ How much variance is there from the mean, and how aggressively does masking need to be to play it safe?



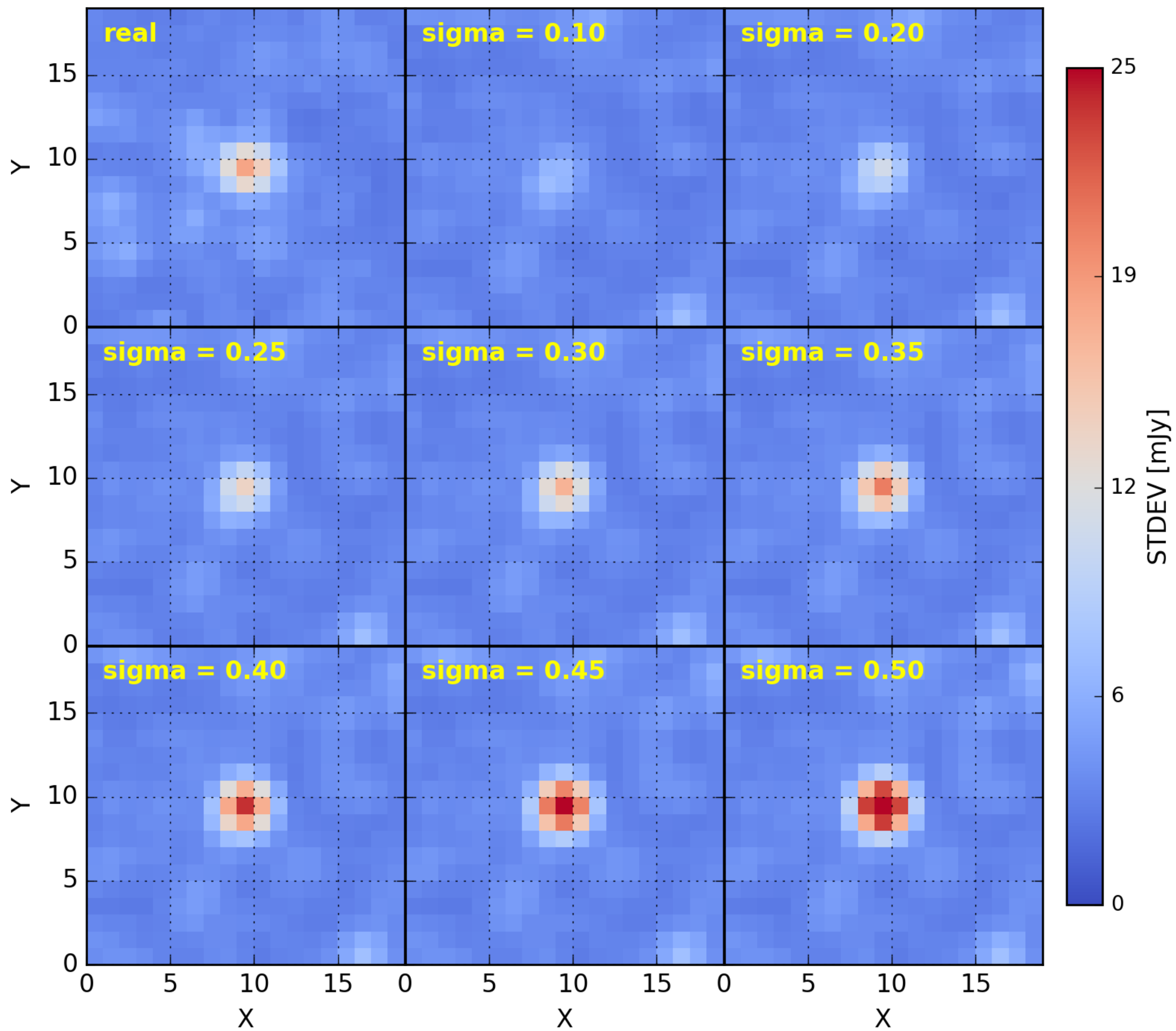
Crites for the Line-Intensity Mapping Status Report — arXiv:1709.09066

CO Foreground Cleaning

Variance in the LIR estimator determined by comparing scatter in the difference map with simulations.

- Find sigma = 0.33

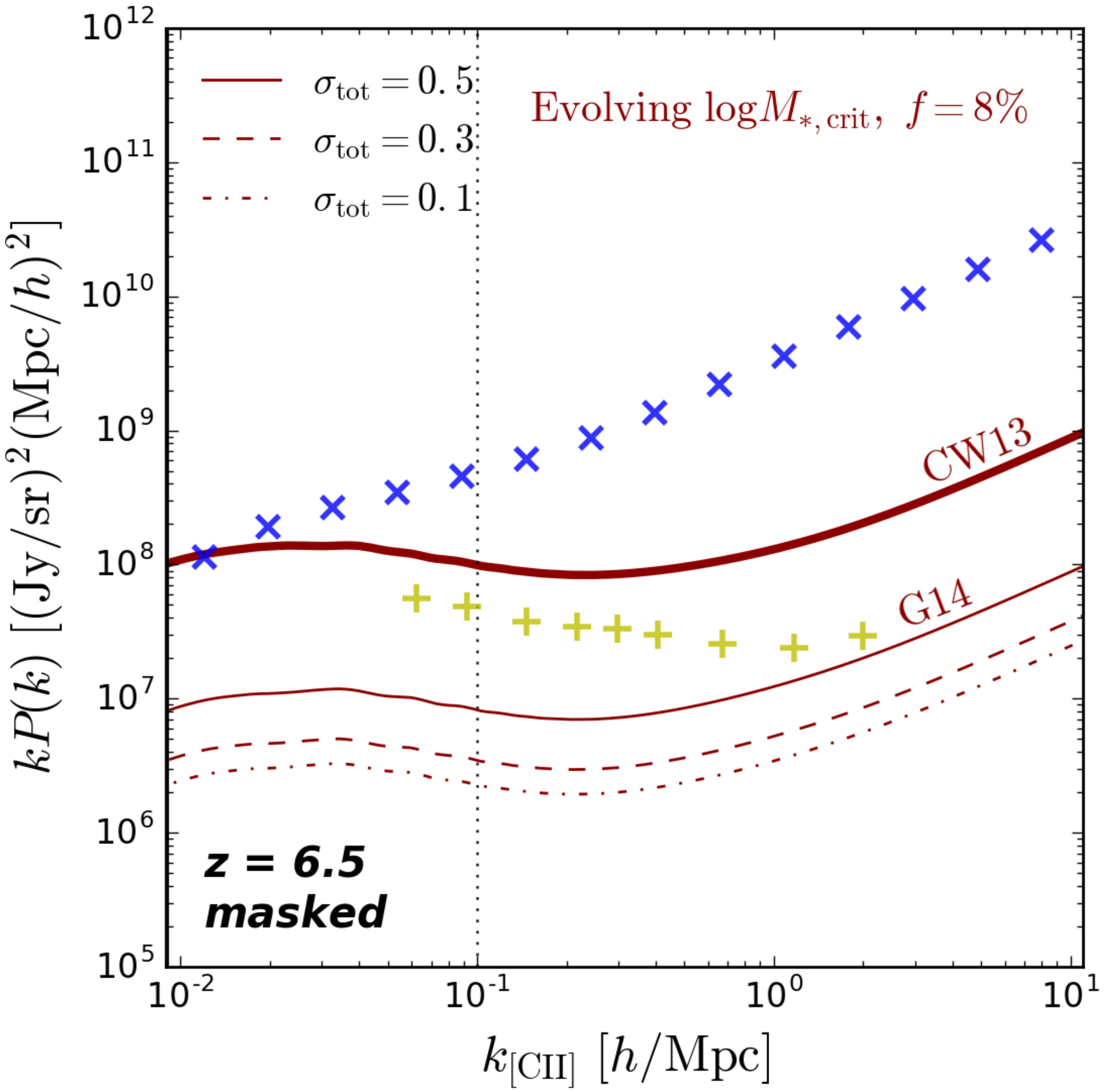
Guaocho (Jason) Sun — Caltech

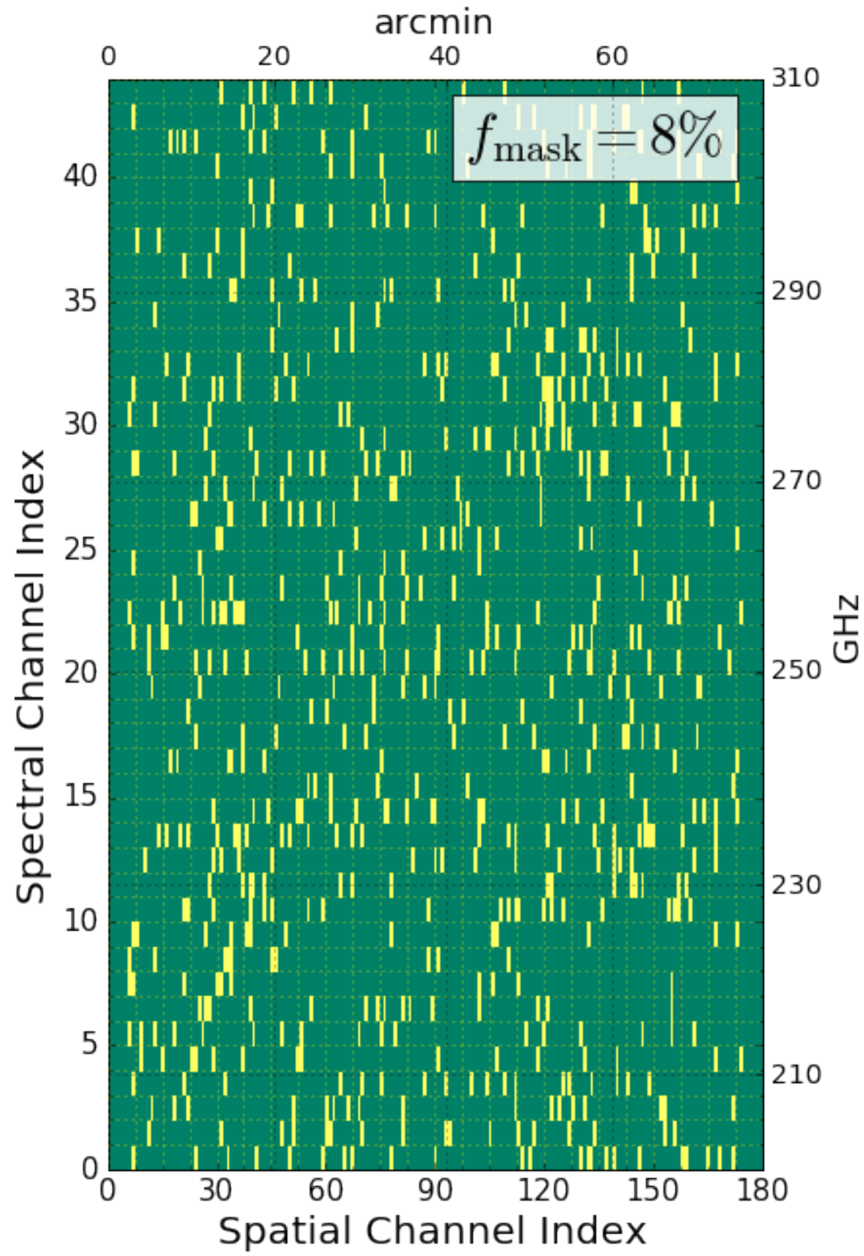


Lorenzo Moncelsi — Caltech

Sun, Moncelsi, Viero & TIME collaboration 2017 — arXiv:1610.10095

CO Foreground Cleaning

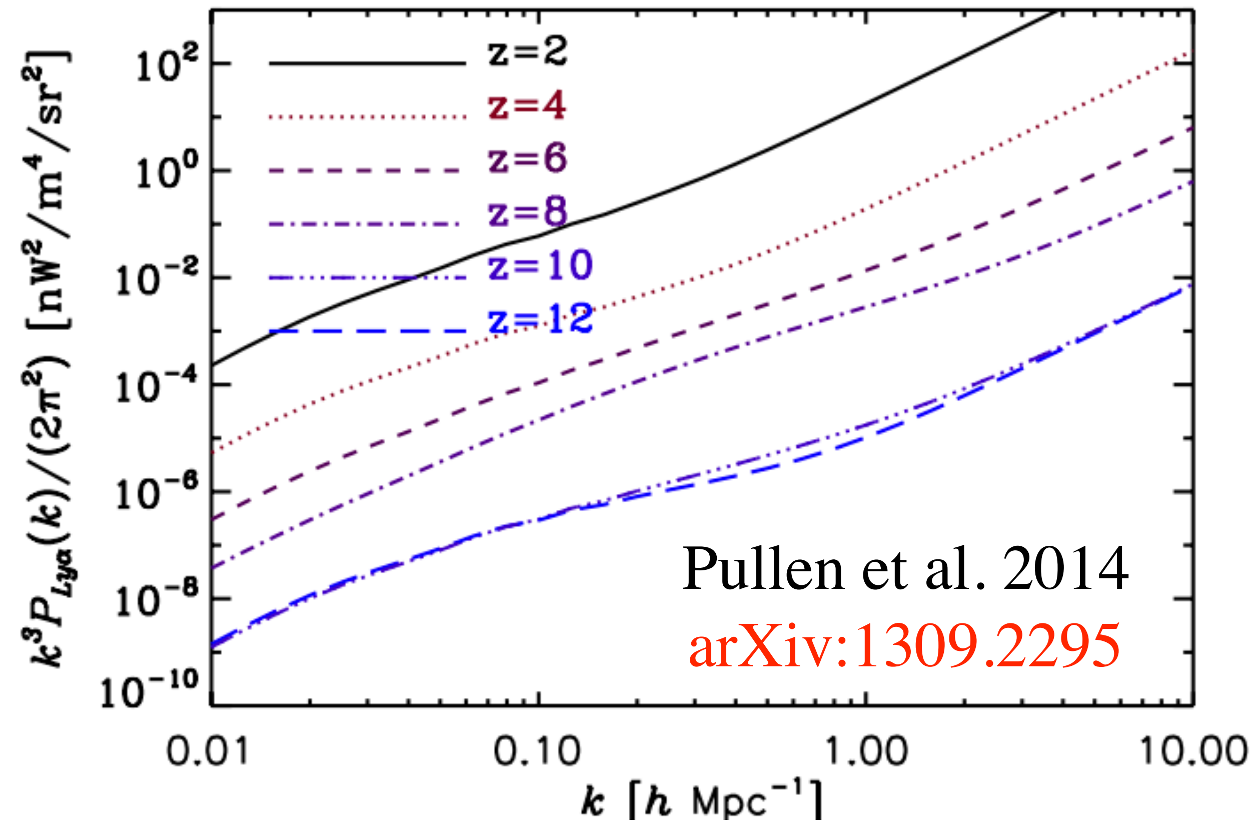


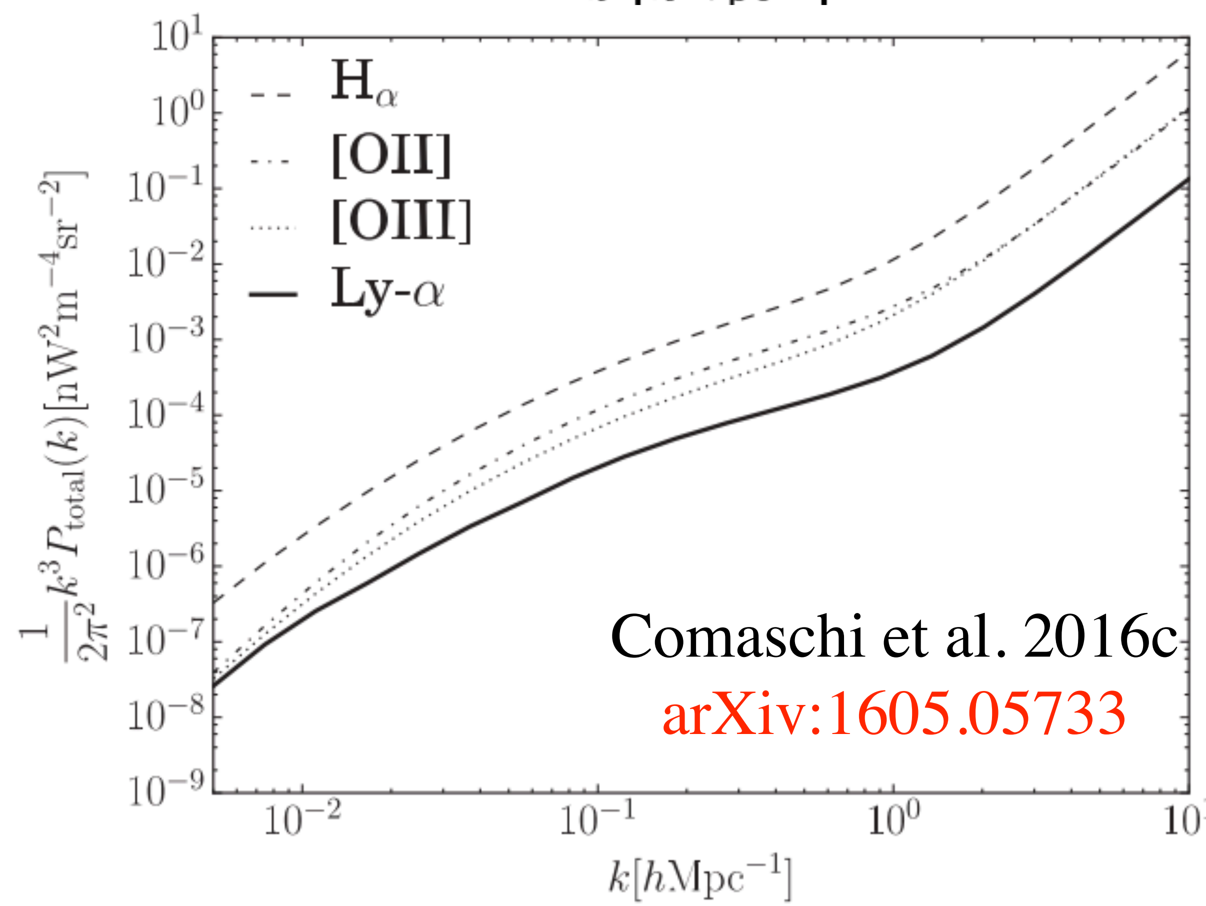


Sun, Moncelsi, Viero & TIME collaboration 2017 — arXiv:1610.10095

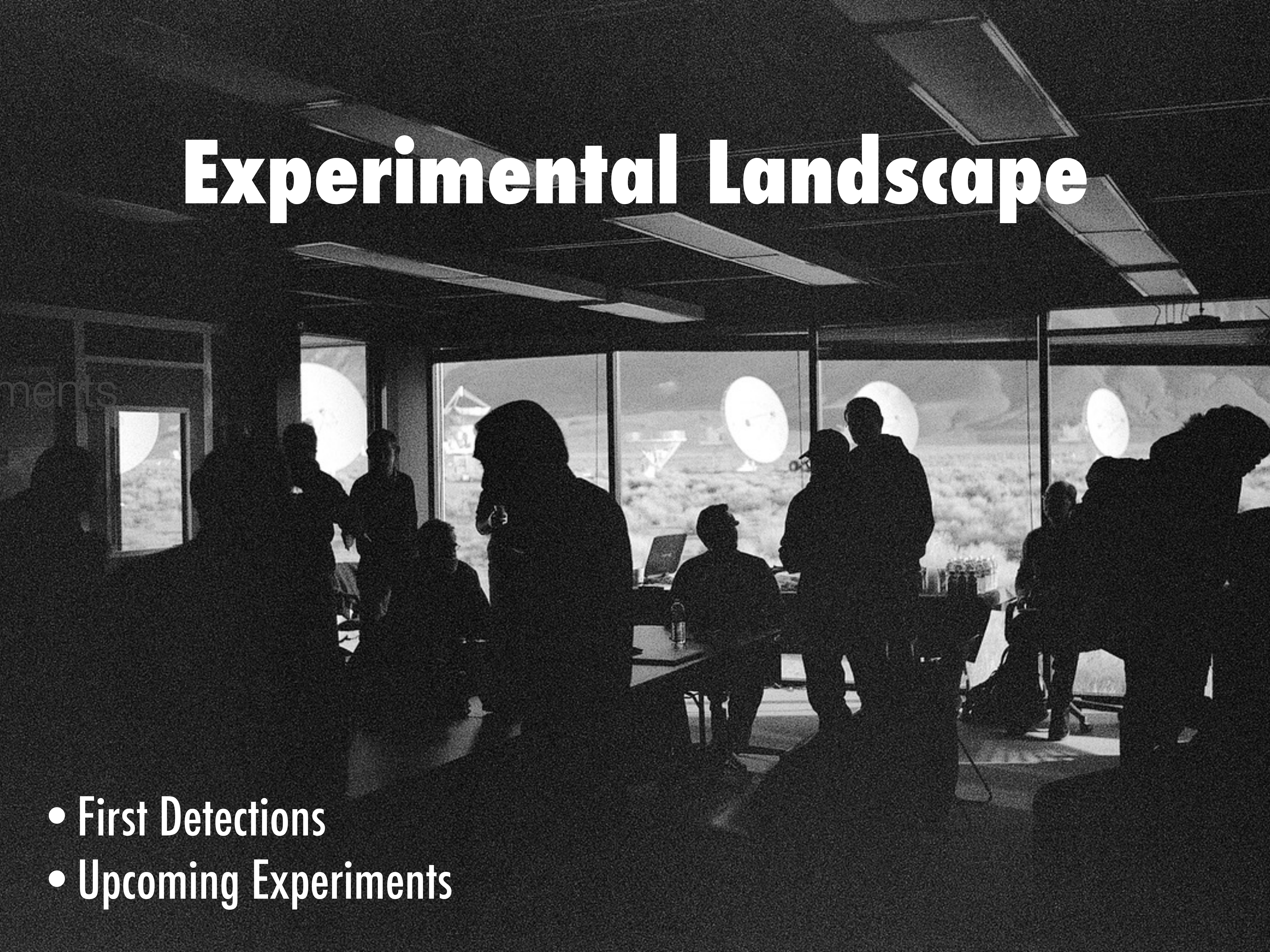
Line-Intensity Mapping — Lyman-alpha

- Lyα is the most luminous UV line.
- High-z Lyα-emitting (LAE) galaxy searches suffer from scattering by HI.
- Intensity mapping sensitive to diffuse ISM
- Interlopers (Hα, [OII], [OIII] present a significant challenge:
  - ➡requires ancillary data to AB mag ~ 26 to identify sources to mask.





Experimental Landscape



- First Detections
- Upcoming Experiments

First Detections: 21cm × Galaxy Surveys at z = 0.8

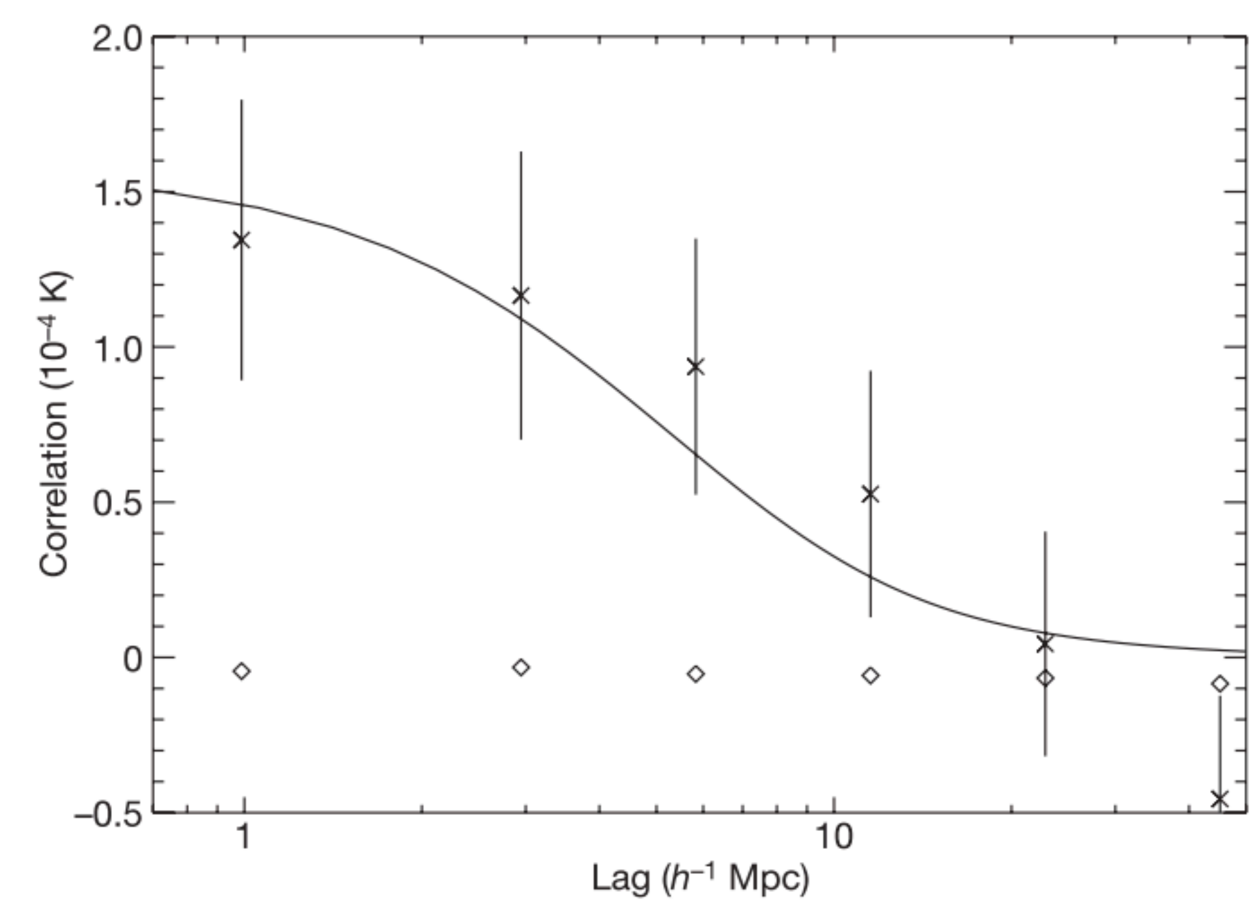
An intensity map of hydrogen 21-cm emission at redshift $z \approx 0.8$

Tzu-Ching Chang[1,2], Ue-Li Pen[2], Kevin Bandura[3] & Jeffrey B. Peterson[3]

Observations of 21-cm radio emission by neutral hydrogen at redshifts $z \approx 0.5$ to ~ 2.5 are expected to provide a sensitive probe of cosmic dark energy[1,2]. This is particularly true around the onset of

(RFI) from terrestrial transmitters and broadband (continuum) emission by astronomical sources within and outside the Milky Way. We use polarization to identify and excise unwanted signals

- Chang+2010 made the first IM detection (**4σ**) by cross-correlating HI intensity map (with GBT 21cm observations of 15 hrs, 2 deg²) with DEEP2 galaxy survey (~10,000 gals) at z = 0.8



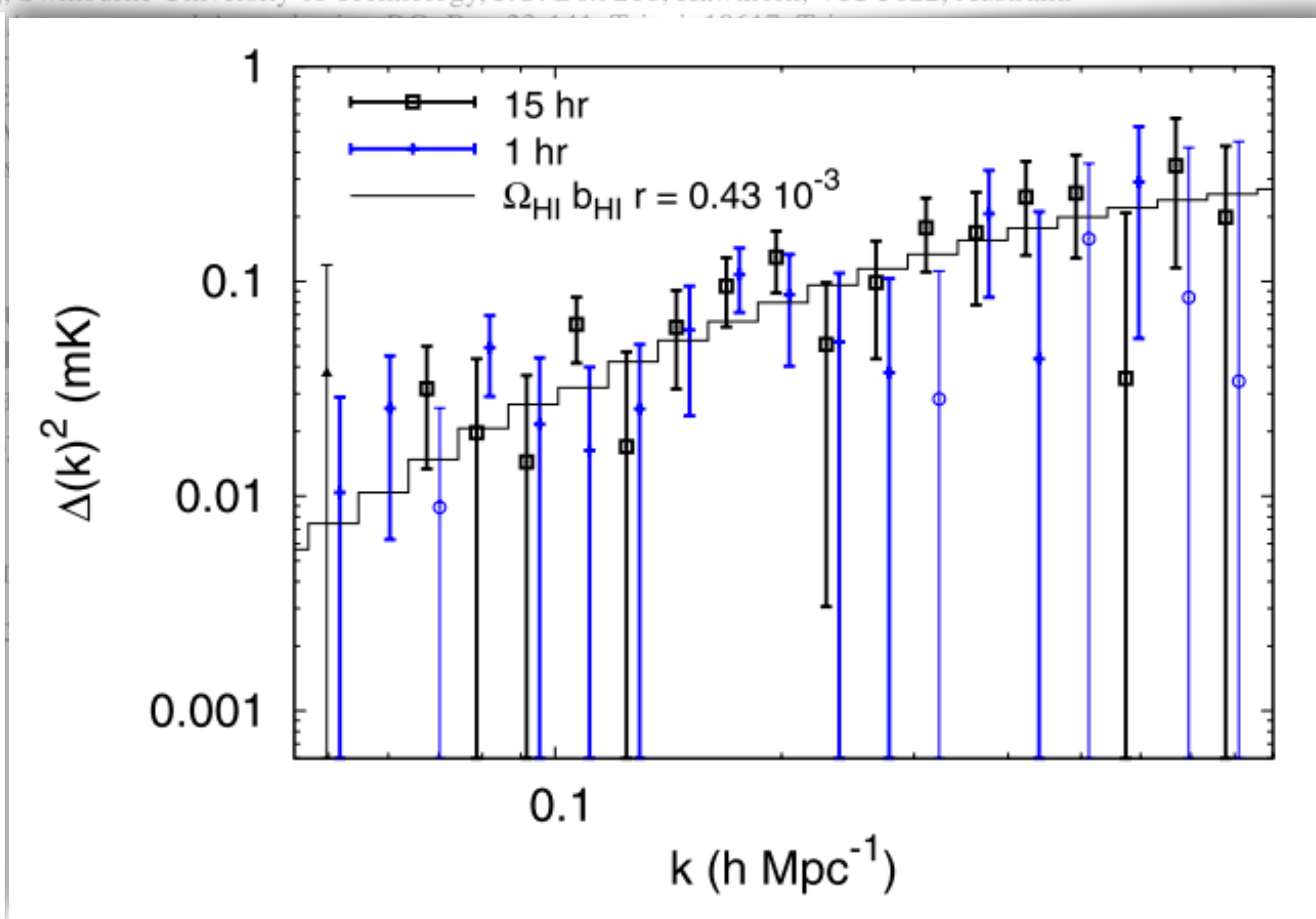
Chang et al. (2010)

First Detections: 21cm × Galaxy Surveys at z = 0.8

MEASUREMENT OF 21 cm BRIGHTNESS FLUCTUATIONS AT $z \sim 0.8$ IN CROSS-CORRELATION

K. W. Masui[1,2], E. R. Switzer[1,3], N. Banavar[4], K. Bandura[5], C. Blake[6], L.-M. Calin[1], T.-C. Chang[7], X. Chen[8,9], Y.-C. Li[8], Y.-W. Liao[7], A. Natarajan[10], U.-L. Pen[1], J. B. Peterson[10], J. R. Shaw[1], and T. C. Voytek[10]
[1] Canadian Institute for Theoretical Astrophysics, University of Toronto, 60 St. George St., Toronto, Ontario, M5S 3H8, Canada
[2] Department of Physics, University of Toronto, 60 St. George St., Toronto, Ontario, M5S 1A7, Canada
[3] Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
[4] Department of Astronomy & Astrophysics, University of Toronto, 50 St. George St., Toronto, Ontario, M5S 3H4, Canada
[5] Department of Physics, McGill University, 3600 Rue University, Montreal, Quebec, H3A 2T8, Canada
[6] Centre for Astrophysics & Supercomputing, Swinburne University of Technology, P.O. Box 218, Hawthorn, VIC 3122, Australia

- Masui+2013 improve upon Chang+2010 measurement, by cross-correlating two fields (deep: 4.5 × 2.4 deg^2, 105hr; wide: 7.0 × 4.3 deg^2, 84hr) and WiggleZ galaxy catalog.



Masui et al. (2013) - arXiv:1208.0331

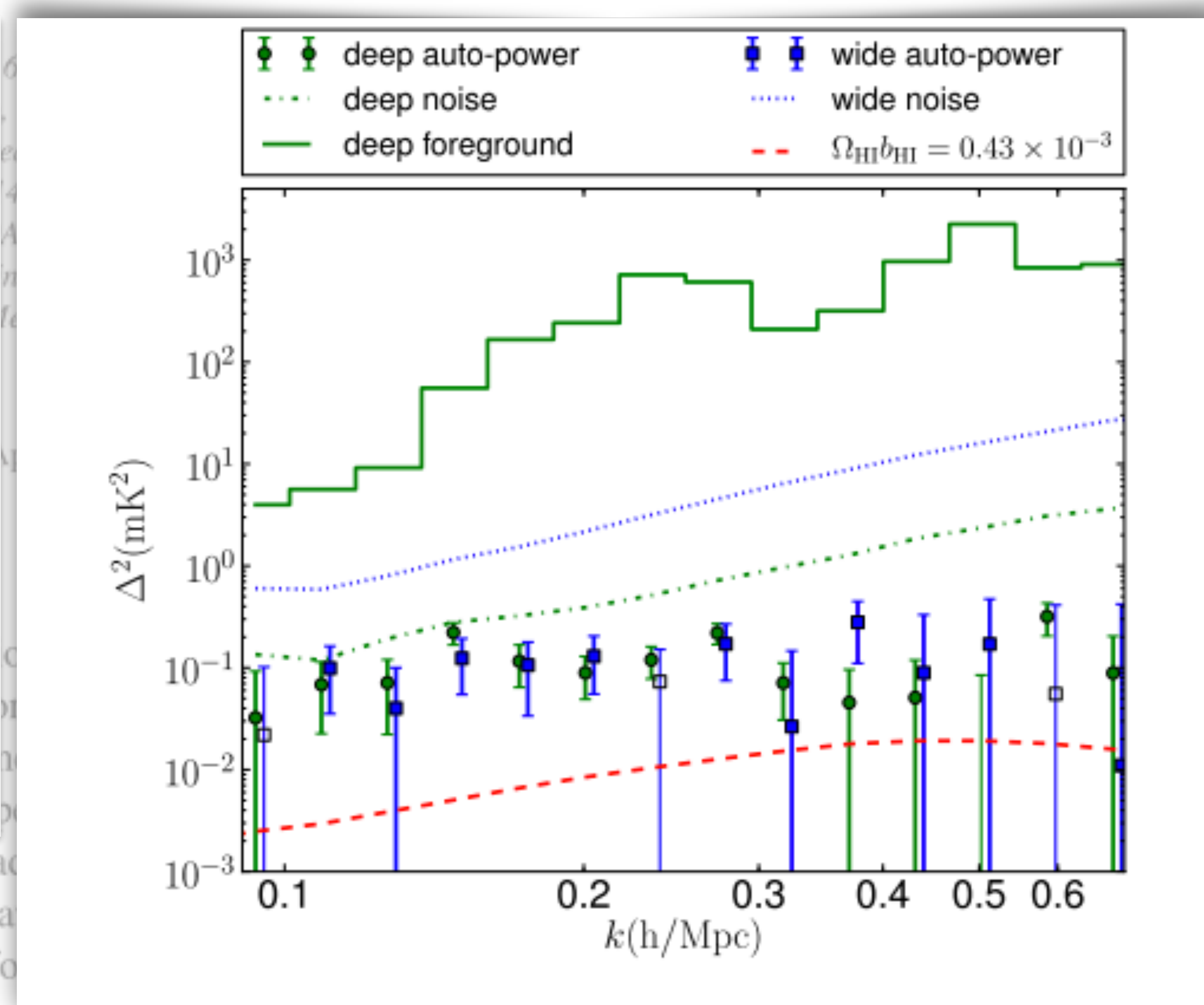
First Detections: 21cm Auto-Spectrum with GBT

Determination of $z \sim 0.8$ neutral hydrogen fluctuations using the 21 cm intensity mapping autocorrelation

E. R. Switzer,[1★] K. W. Masui,[1,2★] K. Bandura,[3] L.-M. Calin,[1] T.-C. Chang,[4] X.-L. Chen,[5,6] Y.-C. Li,[5] Y.-W. Liao,[4] A. Natarajan,[7] U.-L. Pen,[1] J. B. Peterson,[7] J. R. Shaw[1] and T. C. Voytek[7]

- Switzer+2013 claim HI auto-spectrum measurement
- Broadly consistent with cross-correlation, but concerns about foreground residuals after removing to 1 part in 1000

≈41 deg^2 and 190 h of ra
the signal by ~10^3, but ha
the presence of residual fo
on the 21 cm signal. Our

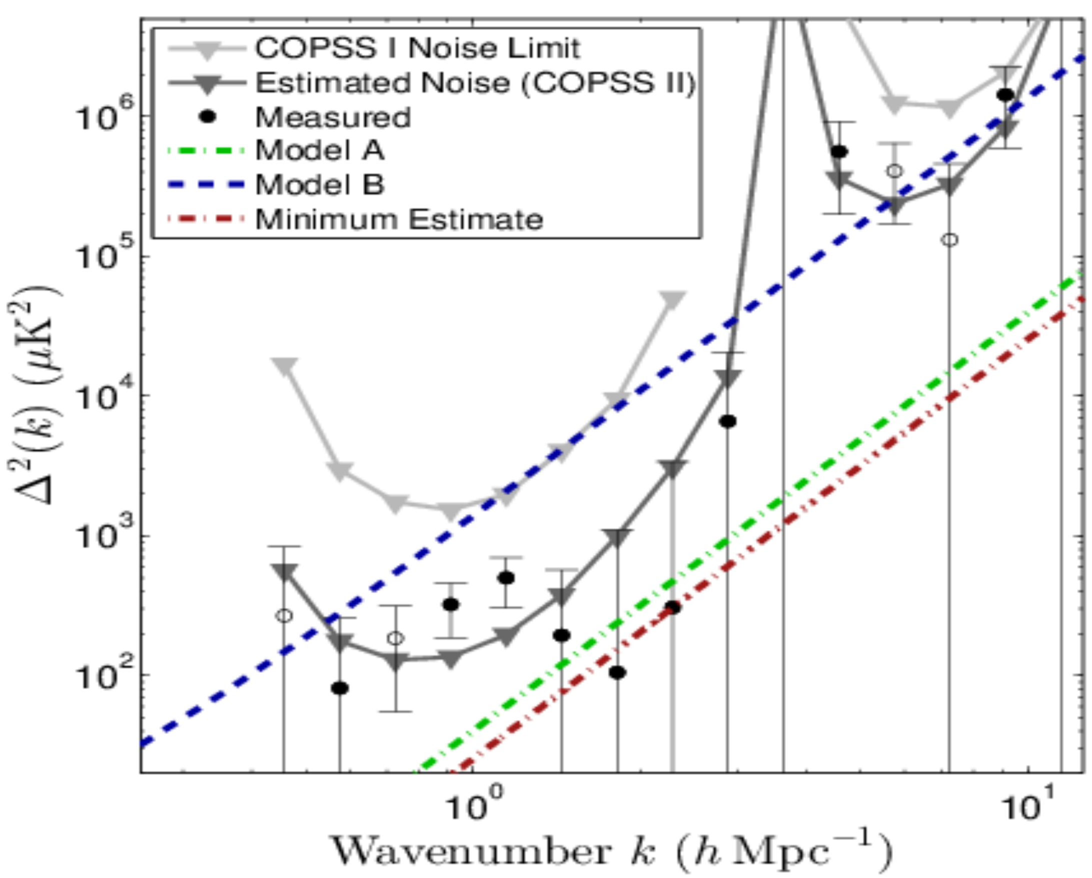


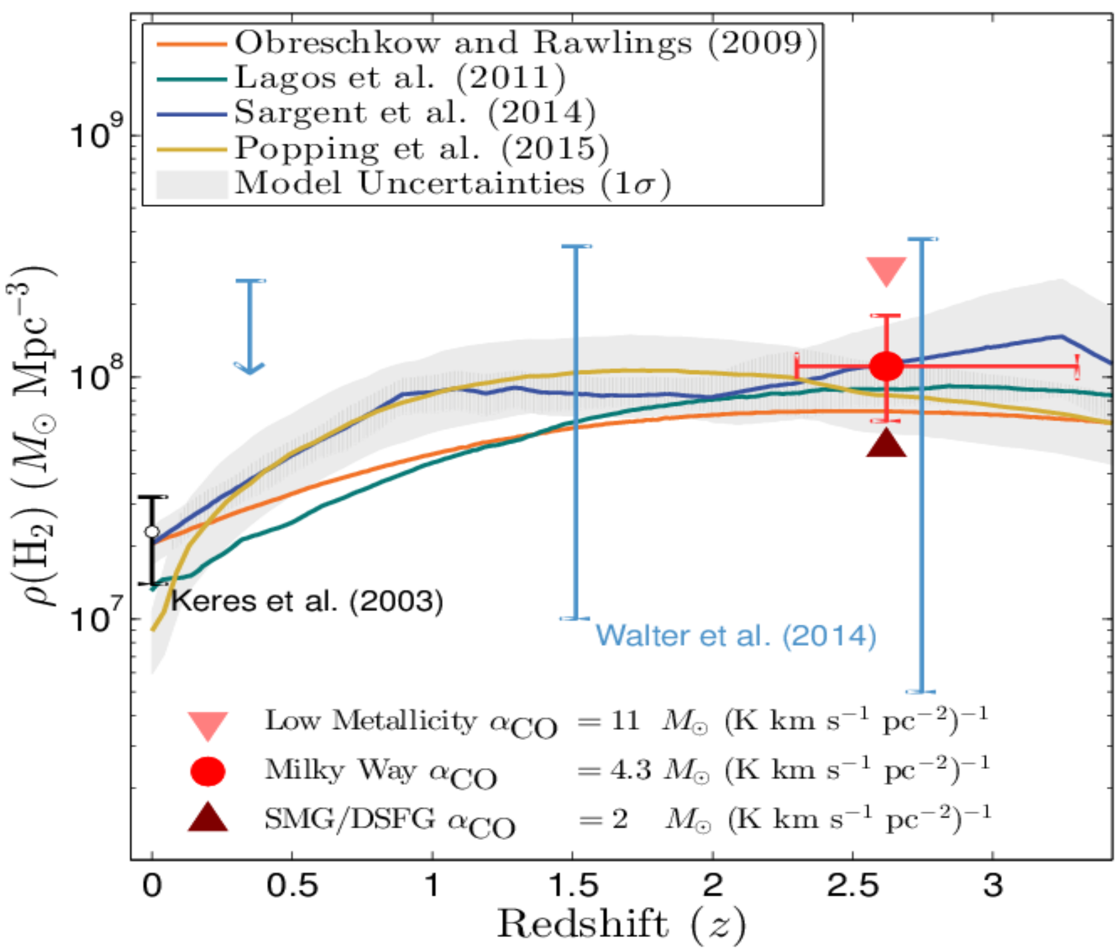
Switzer et al. (2013) - arXiv:1304.3712

First Detections: CO Power Spectrum Survey (COPSS)

COPSS II: THE MOLECULAR GAS CONTENT OF TEN MILLION CUBIC MEGAPARSECS AT REDSHIFT $z \sim 3$

- Targeting CO(1-0) at z ~ 3 with SZA (27-35GHz).
- Tentative detection (2.5σ) combining:
  - ➡ archival data (1,400 hrs, 44 fields; **Keating et al. 2015**)
  - ➡ dedicated observing campaign (5,000 hrs, 12 fields; **Keating et al. 2016**)
- Results suggest models under-predict abundance of CO emitters at z = 2-3.





Experimental Landscape

Experiment	Line	Frequency	Redshift range	Location
HERA	HI	$50 - 250\,\mathrm{MHz}$	$5 - 27$	South Africa
SKA-LOW	HI	$50 - 350\,\mathrm{MHz}$	$3 - 7$	Australia
CCAT-prime	[CII]	$185 - 440\,\mathrm{GHz}$	$3.3 - 9.3$	Chile
TIME	[CII]	$200 - 300\,\mathrm{GHz}$	$5.3 - 8.5$	North America
CONCERTO	[CII]	$200 - 360\,\mathrm{GHz}$	$4.3 - 8.5$	Chile
COPSS	CO	$27 - 35\,\mathrm{GHz}$	$2.3 - 3.3$	North America
mmIME	CO, [CII]	$300, 100, 30\,\mathrm{GHz}$	$1 - 5$	various
AIM-CO	CO	$86 - 102\,\mathrm{GHz}$	$1.2 - 1.7,\ 2.4 - 3.0$	China
COMAP	CO	$26 - 34\,\mathrm{GHz}$	$2.4 - 3.4,\ 5.8 - 7.8$	North America
STARFIRE	[CII], NII	$714 - 1250\,\mathrm{GHz}$	$0.5 - 1.5$	Sub-orbit (balloon)
SPHEREx	Hα (Hβ, [OII] [OIII]), Lyα	$60 - 400\,\mathrm{THz}$	$0.1 - 5,\ 5.2 - 8$	Space
CHIME	HI	$400 - 800\,\mathrm{MHz}$	$0.8 - 2.5$	North America
HIRAX	HI	$400 - 800\,\mathrm{MHz}$	$0.8 - 2.5$	South Africa
SKA-MID	HI	$350\,\mathrm{MHz} - 14\,\mathrm{GHz}$	$0 - 3$	South Africa
BINGO	HI	$939 - 1238\,\mathrm{MHz}$	$0.13 - 0.48$	South America

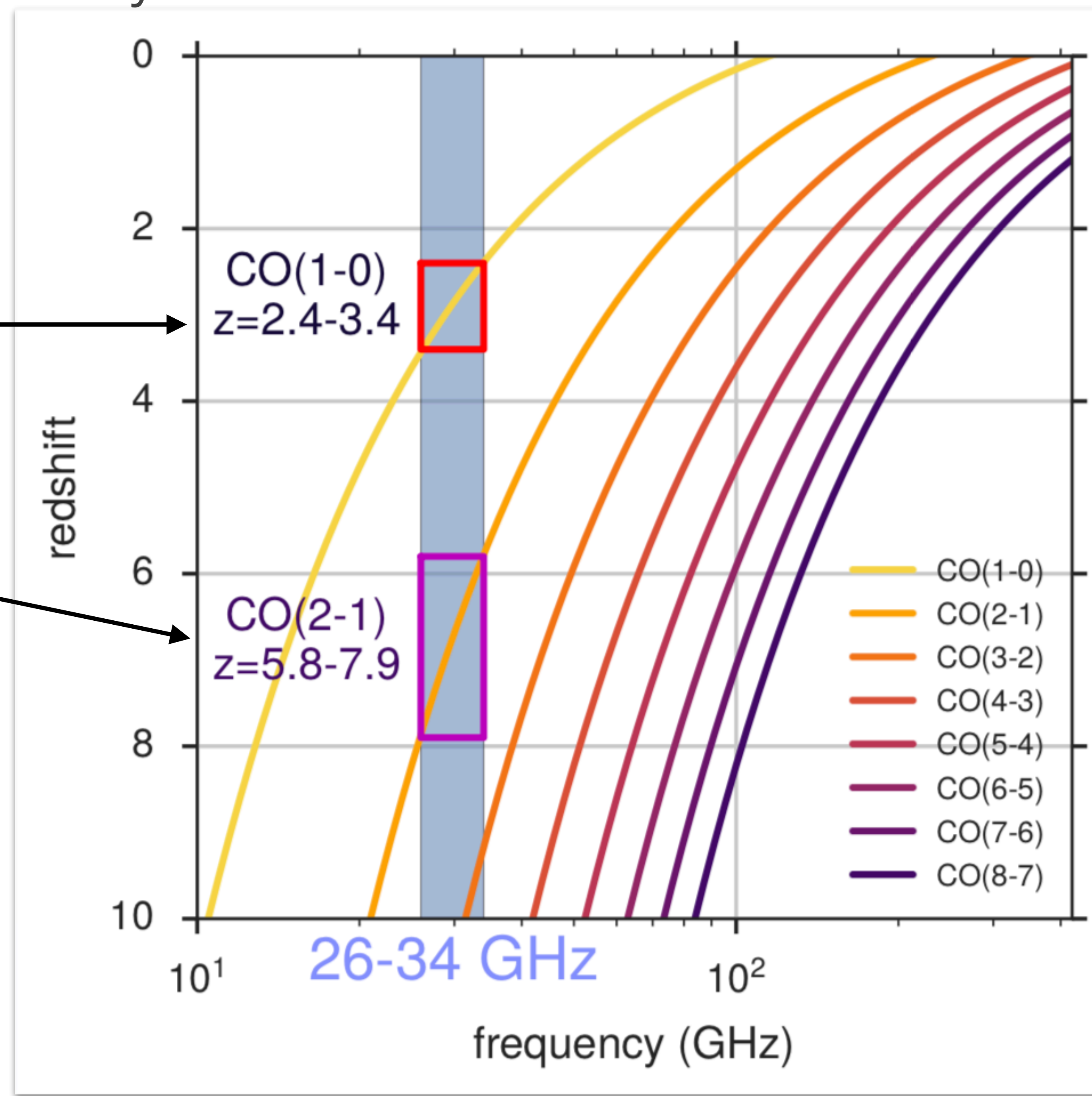
From the Line-Intensity Mapping Status Report (Kovetz, Viero et al. 2017 — arXiv:1709.09066)

COMAP

Caltech	Kieran Cleary [PI] Tony Readhead Tim Pearson James Lamb David Woody	UiO : Universitetet i Oslo	Hans Kristian Eriksen Ingunn Wehus Marie Foss Håvard Ihle
Stanford	Sarah Church Risa Wechsler Marco Viero Dongwoo Chung	MANCHESTER 1824 The University of Manchester	Clive Dickinson Stuart Harper
JPL	Tzu-Ching Chang Todd Gaier Charles Lawrence Brandon Hensley	CITA ICAT	J Richard Bond Norm Murray Marcelo Alvarez Gunjan Lakhlani George Stein
University of Maryland	Andrew Harris	ETH zürich	Hamsa Padmanabhan
University of Miami	Joshua Gundersen		

COMAP

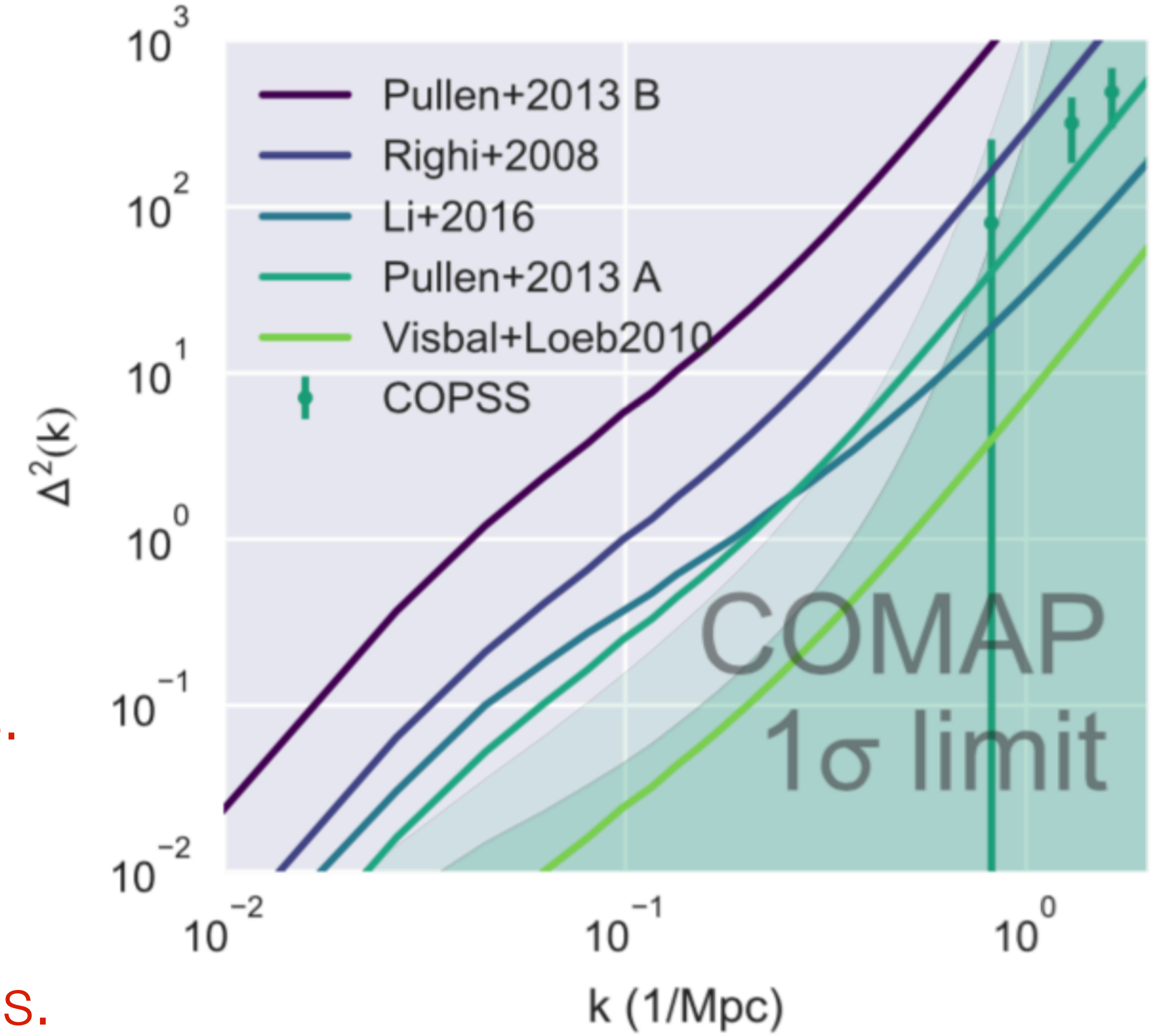
- 10 m telescope (formerly CARMA) at Owens Valley Radio Observatory
- 19 pixel, 26-34 GHz
- Targeting:
  - ➡ CO(1-0)
    - z = 2.4-3.4: peak galaxy assembly
  - ➡ CO(2-1)
    - z=5.8-7.9: EoR



Courtesy Dongwoo Chung

COMAP

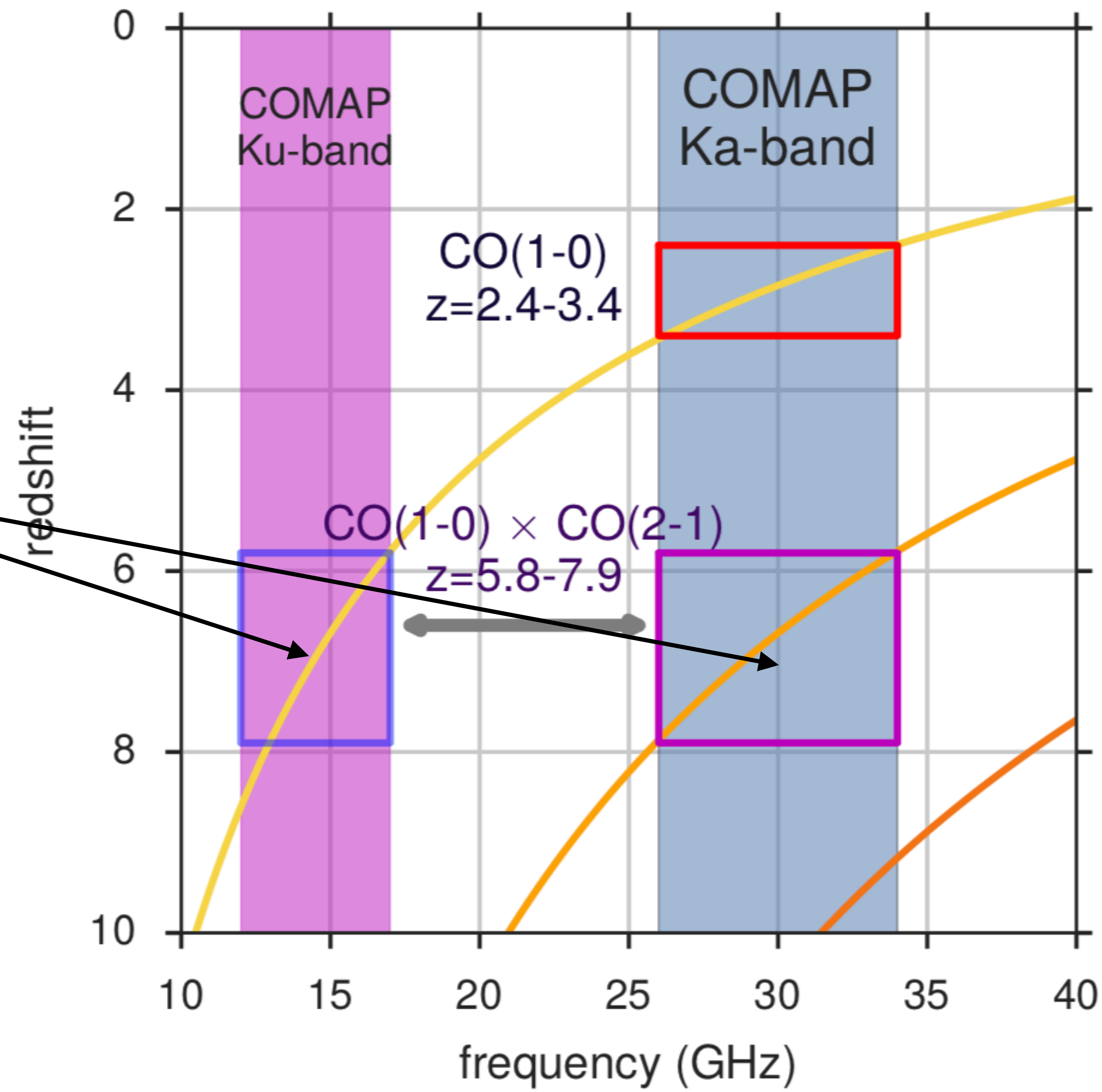
- 10 m telescope (formerly CARMA) at Owens Valley Radio Observatory
- 19 pixel, 26-34 GHz
- Targeting:
    - ➡CO(1-0)
        - z = 2.4-3.4: peak galaxy assembly
    - ➡CO(2-1)
        - z=5.8-7.9: EoR
- Phase I
    - ➡1 telescope, 2 years, 3 fields.
    - ➡Project >**3σ** detection.
- Phase II
    - ➡5 telescopes, 3 years, 3 fields.
    - ➡Project >>**5σ** detection.



Courtesy Dongwoo Chung

COMAP

- Phase III (z = 5.8-7.9)
- Addition of 12-17 GHz (Ku-band)
- Targeting:
  - ➡CO(1-0)
    - z = 5.8-7.9: EoR
  - ➡Cross-correlate to distinguish high-z signal from lower-z foreground in Ka-band



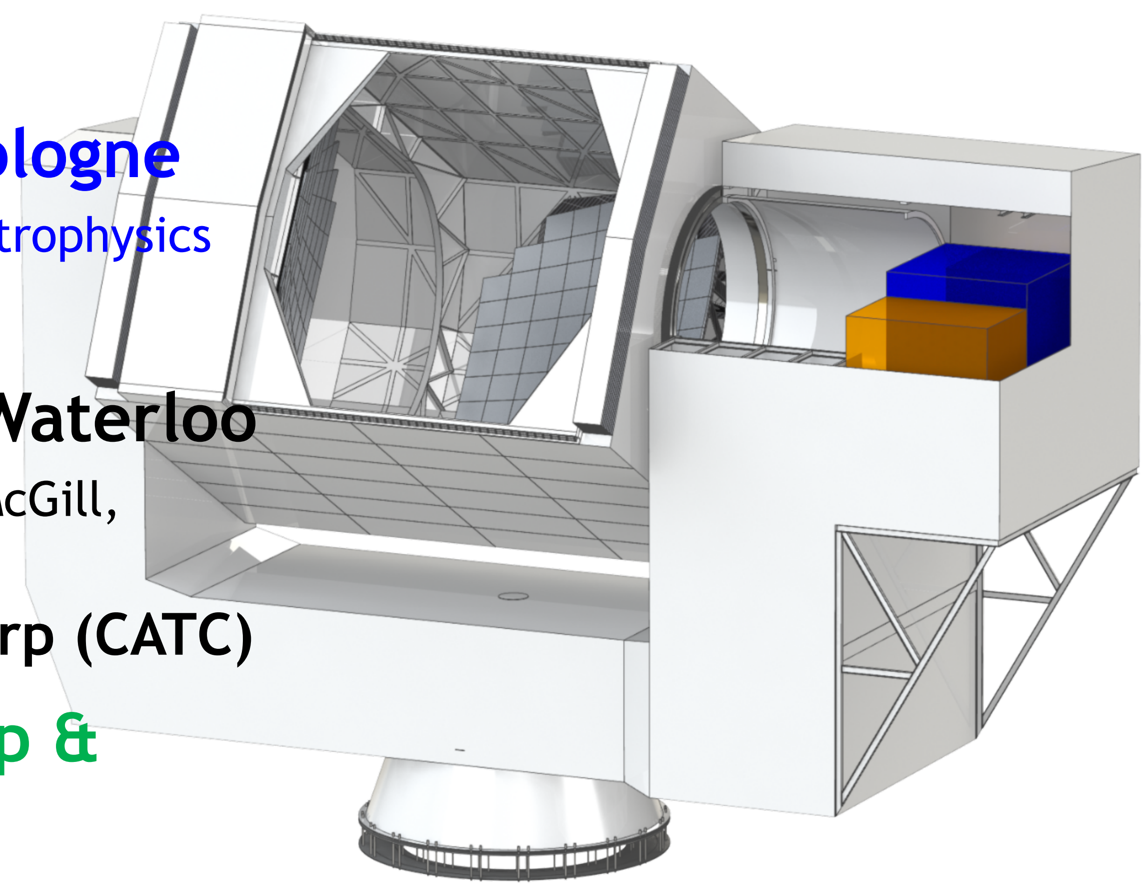
Courtesy Dongwoo Chung

- COMAP commissioning underway:
  - ➡First light expected early 2018.

CCAT-prime

- **Cornell University**
- **German consortium led by University of Cologne**
  - Cologne, Bonn, Ludwig Maximilian, Max Planck Inst. for Astrophysics
    - ❖ **Formed CCAT Observatory, Inc.**
- **Canadian consortium led by University of Waterloo**
  - Waterloo, Toronto, British Columbia, Calgary, Dalhousie, McGill, McMaster, Western Ontario
    - ❖ **Formed Canadian Atacama Telescope Corp (CATC)**

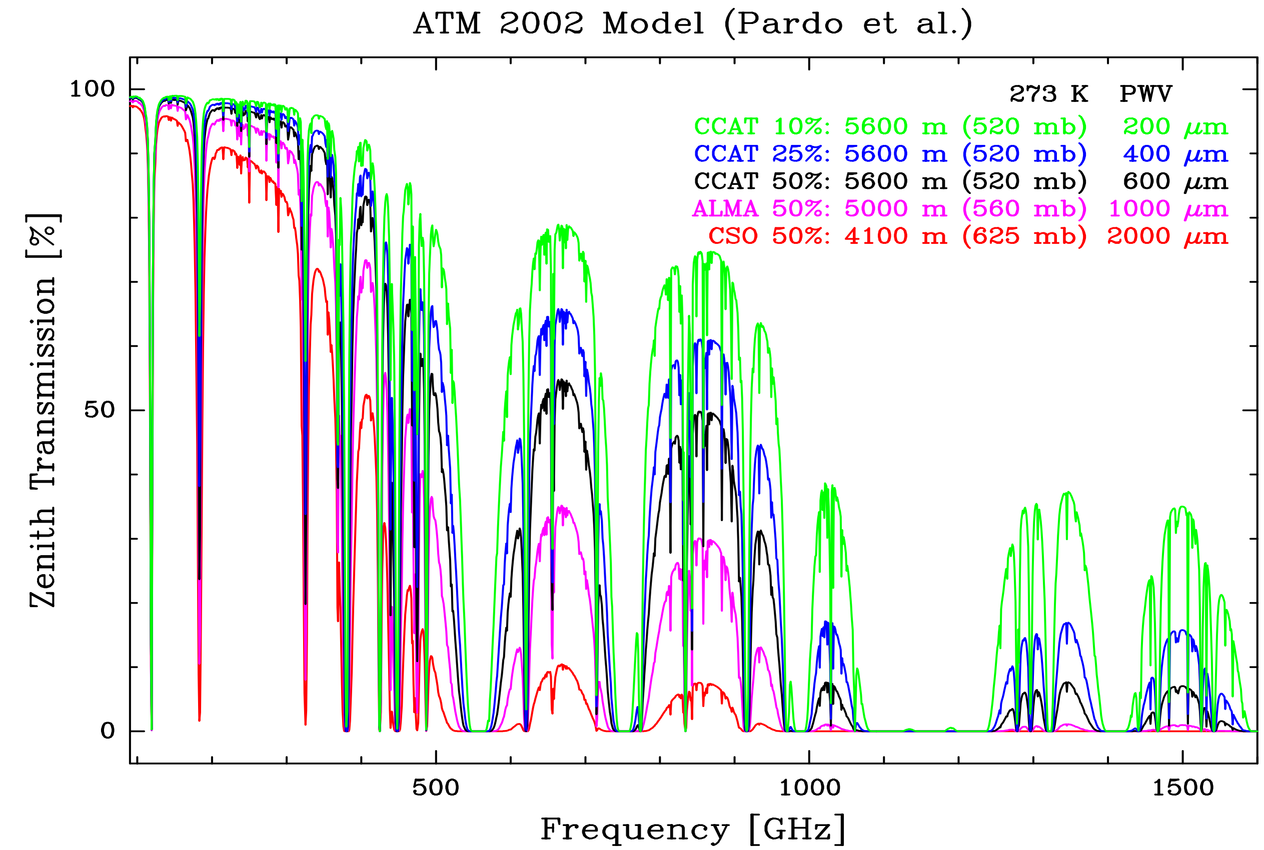
❖ **CCAT is a Joint Venture between CCAT Corp & CATC**



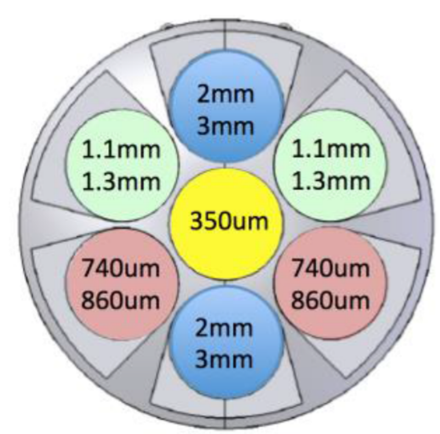
Stacey for the Line-Intensity Mapping Status Report — arXiv:1709.09066

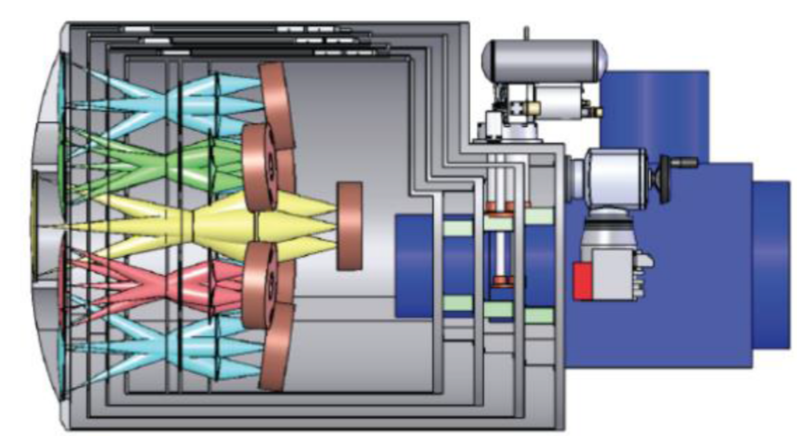
CCAT-prime — Intensity Mapping of CII at High-z

- 6 m crossed Dragone telescope design (Niemack et al. 2015)
- High accuracy (11 μm rms) and throughput optimized for high surface brightness sensitivity.
- ~5 deg FOV
- 20-60,000 pixels per subcamera
- Optimal for science enabled by large-scale (e.g., line-intensity mapping) surveys.
- Will observe [CII] 157 μm line:
    - ➡z = 3.3-9.3.
    - ➡~4000 hr over 5 years.
    - ➡16 deg² (COSMOS, UDS, and/or Euclid)

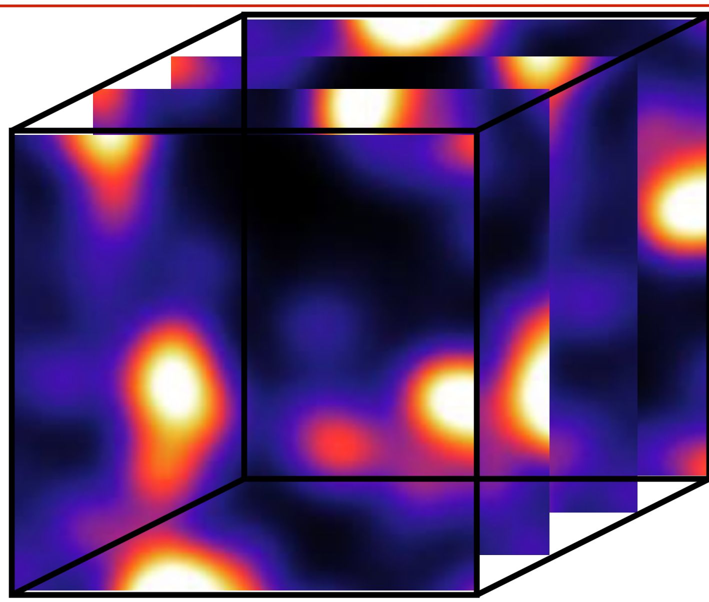


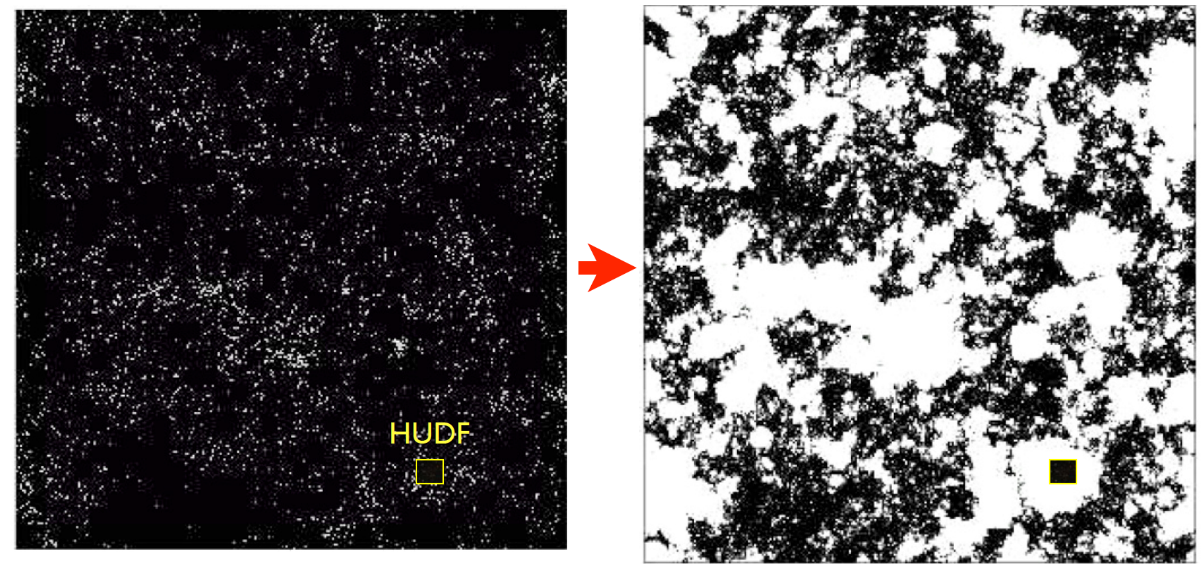
P-CAM





TIME — Tomographic Ionized-Carbon IM Experiment





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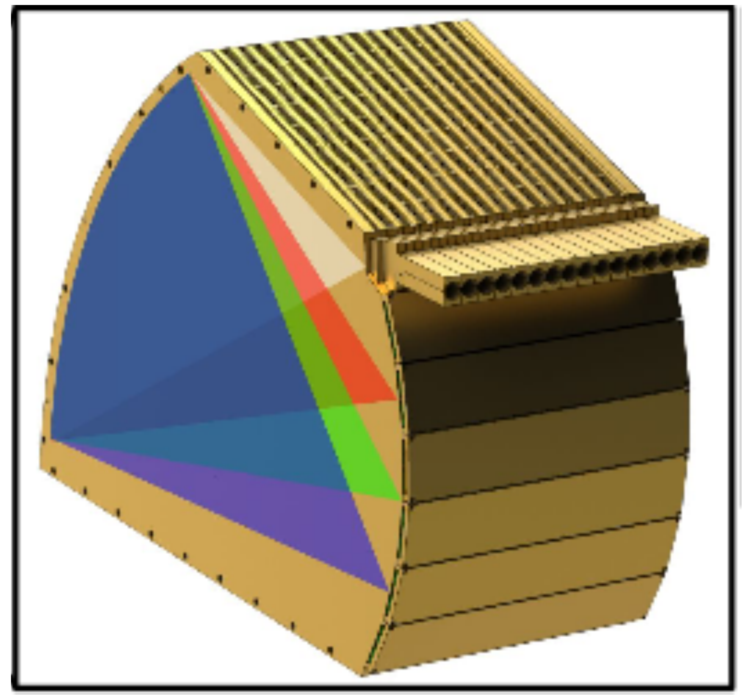
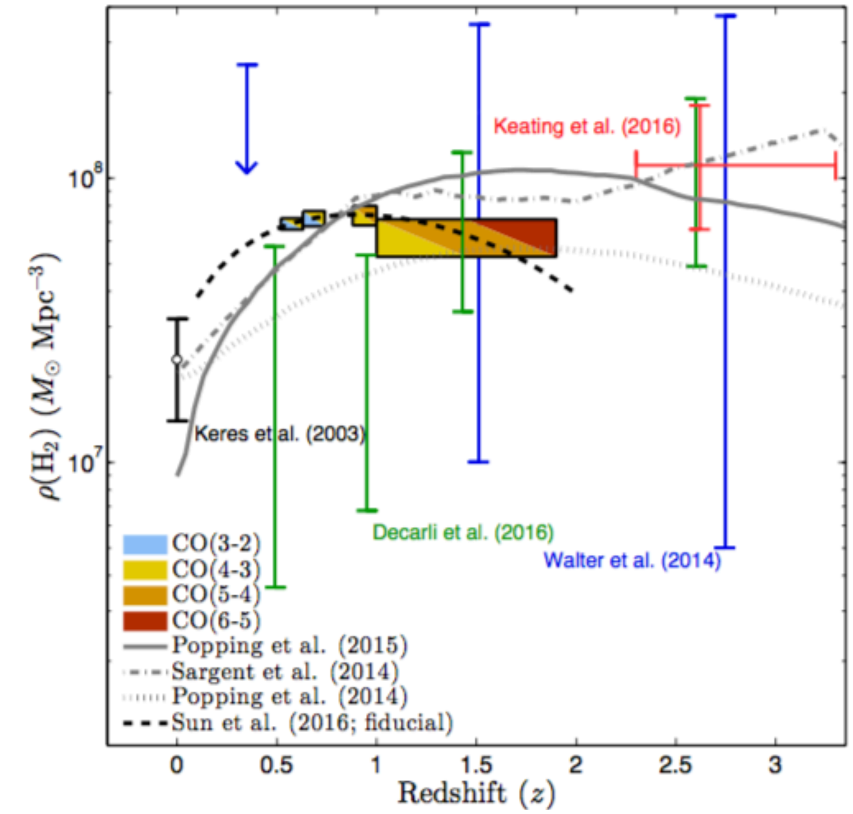
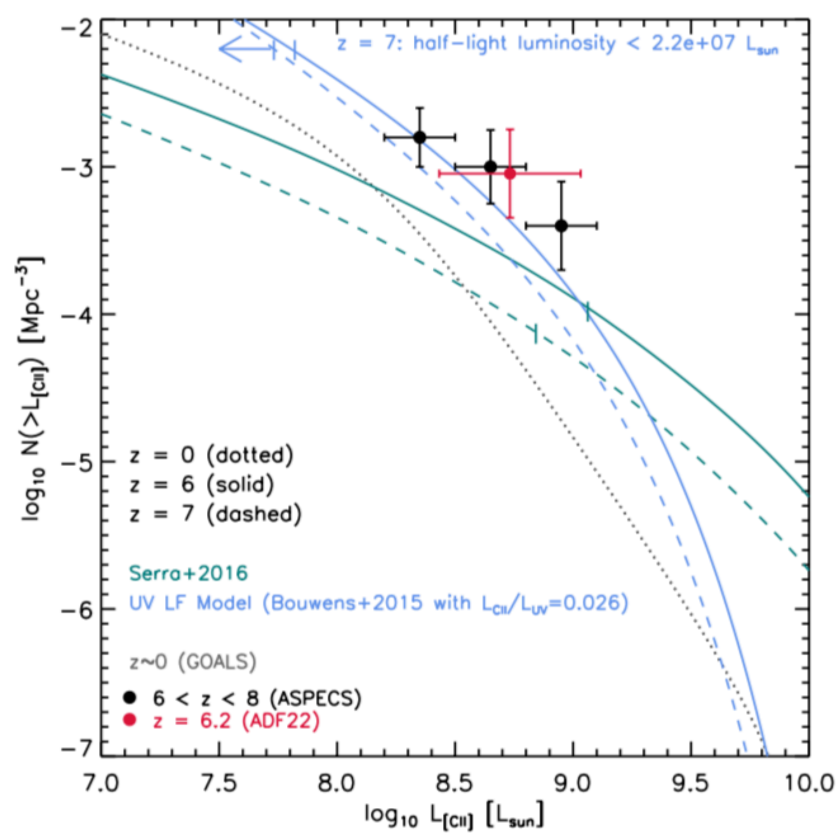
Dan Marrone
Isaac Trumper
Karto Keating

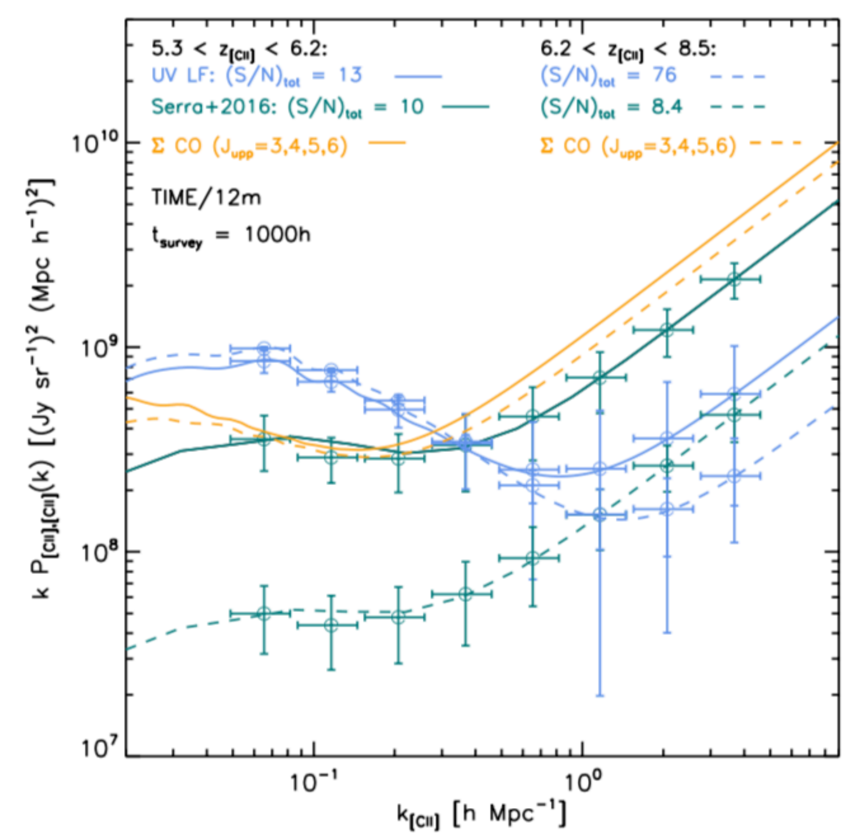
TIME — Tomographic Ionized-Carbon IM Experiment

- Targeting:
  - ➡ CII
    - z = 6-8: EoR
  - ➡ CO(2-1)
    - z = 1-2: peak galaxy assembly
- Instrument
  - ➡ 2x16 Grating Spectrometers
  - ➡ 2000 Transition Edge Sensor Bolometers (TESs)
  - ➡ Spectrometer resolution ~ 100



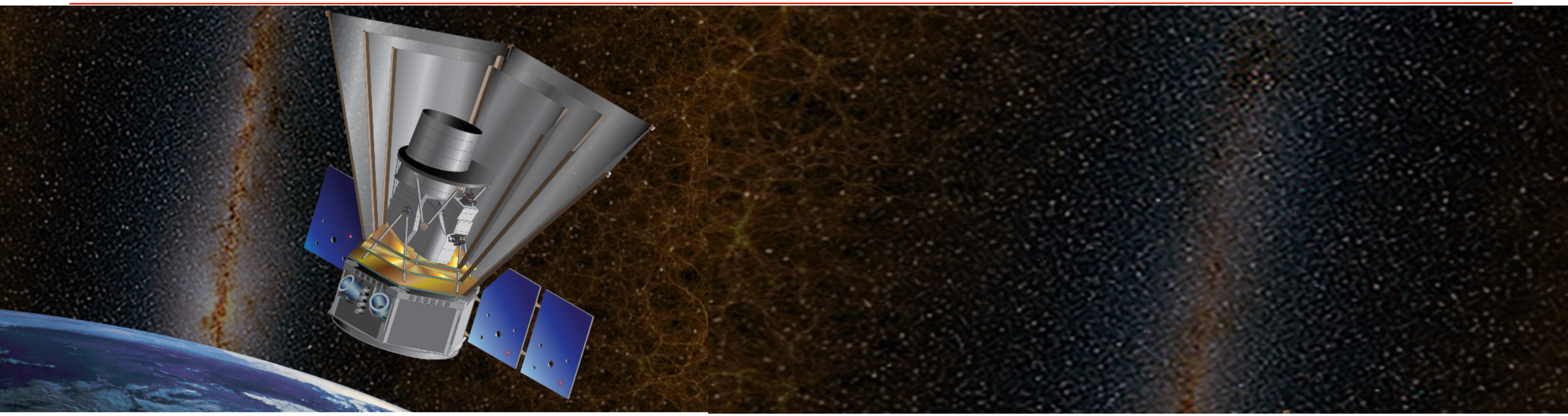






Bock for the Line-Intensity Mapping Status Report — arXiv:1709.09066

SPHEREx



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Philip Korngut
Peter Capak
Dan Masters

Argonne National Laboratory
Salmon Habib
Katrin Heitmann
Lindsey Bleem

Ohio State
Chris Hirata

R·I·T
Michael Zemcov

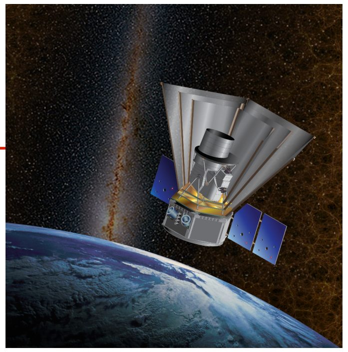
And many more..

JPL
Olivier Doré
Steve Unwin
Michael Werner
Roland de Putter
Tim Eifler
Hien Nguyen
Brandon Crill
Tzu-Ching Chang

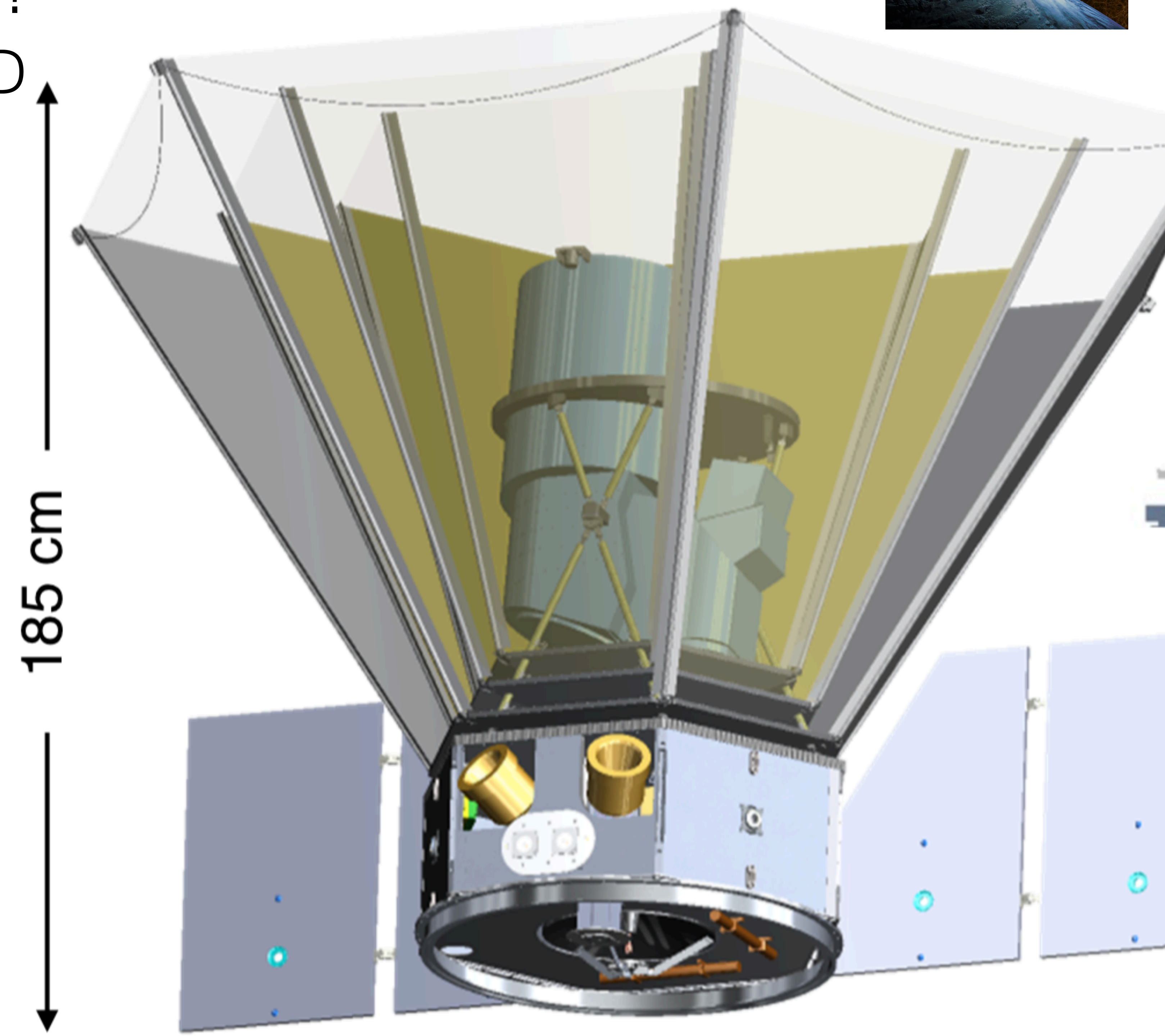
UC Irvine
Asantha Cooray
Yan Gong

Stanford
Elisabeth Krause
Marco Viero

SPHEREx — All Sky Spectral Survey

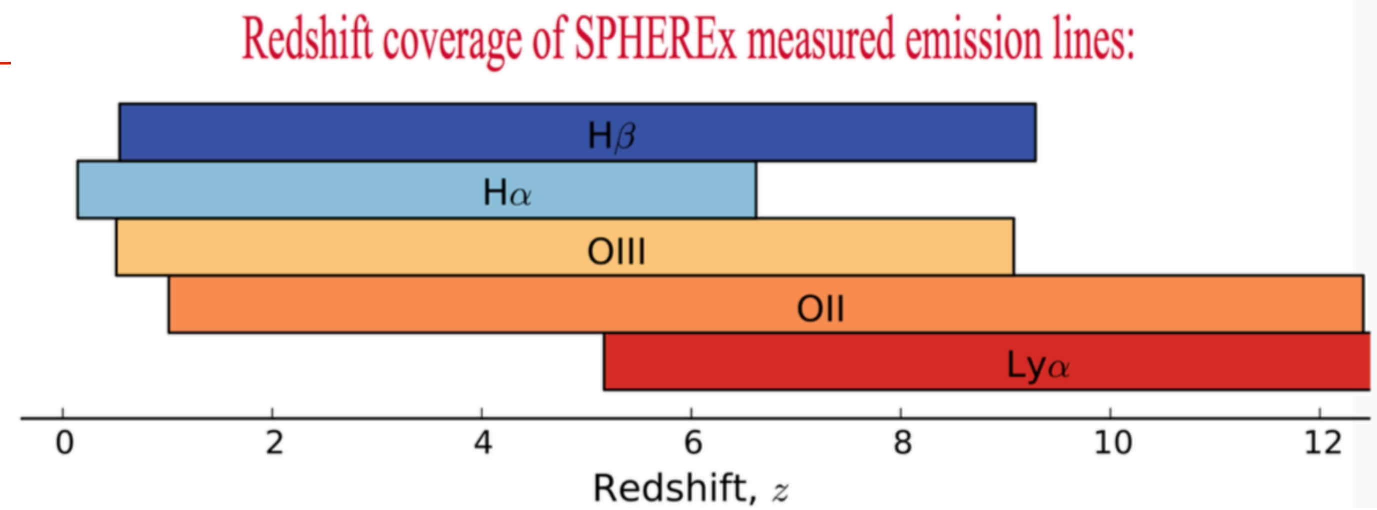


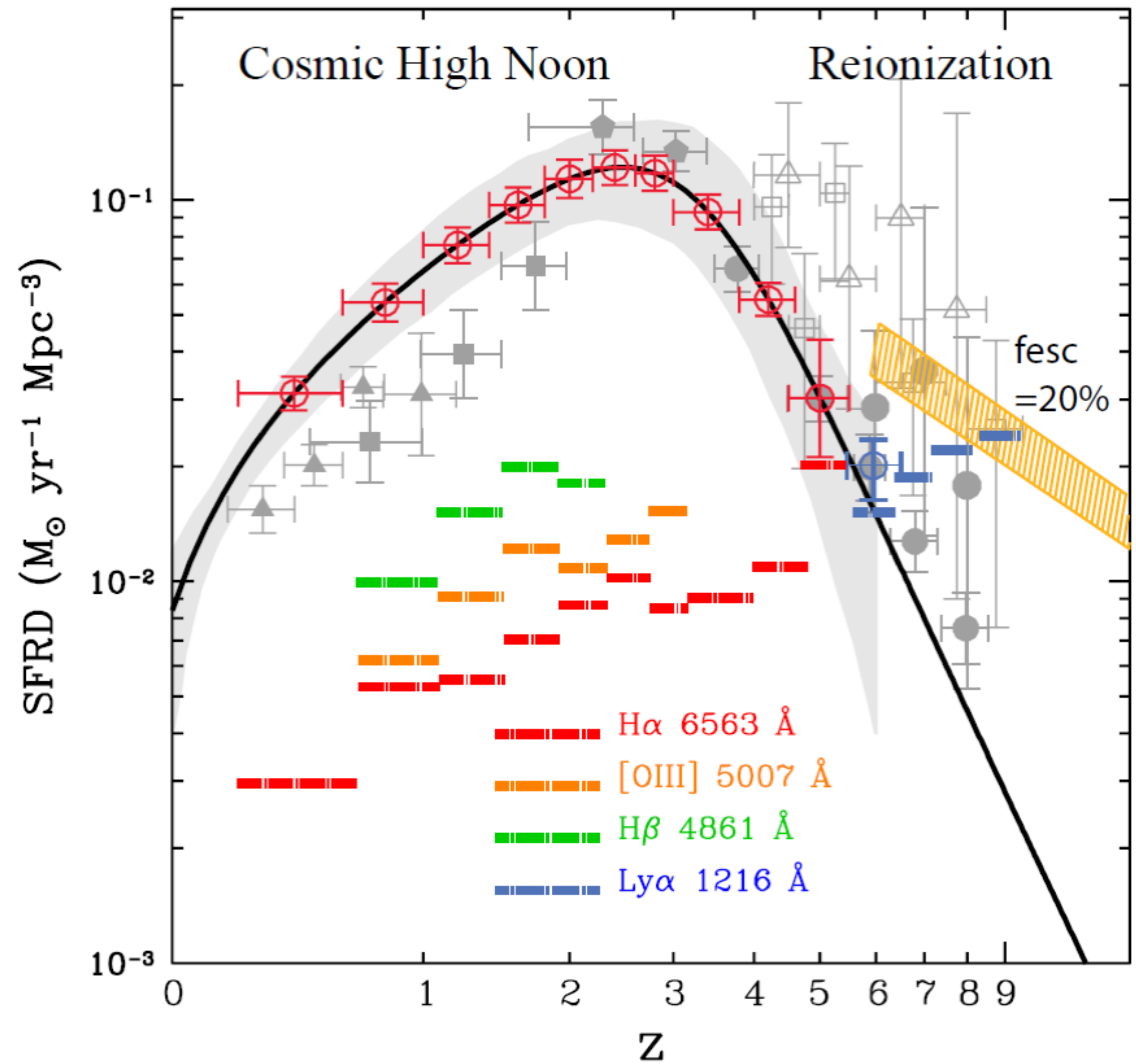
- How did the Universe Begin?
  - ➡Probe Inflation through 3D clustering of galaxies
- How did Galaxies Form?
  - ➡Measure Extragalactic Background Light (EBL) with intensity mapping to probe EoR
- What are the conditions for Life outside Solar System?
  - ➡Measure ice absorption features interstellar ices bring water and organic molecules into proto-planetary systems.



SPHEREx

- All-sky spectral survey:
  - ➡20 cm telescope
  - ➡3.5° x 7° FOV
  - ➡6″ pixels
  - ➡λ = 0.75 – 5 μm
  - ➡λ/Δλ = 41.5 & 135 (96 channels)
- 100 square degree deep-fields targeting:
  - ➡Hα, Hβ, OIII at z=0.5-5
  - ➡Probes Lyα at z > 5
- NASA MIDEX Phase A finalist (decision pending)





Summary

- Since reionization is likely dominated by faint galaxies below the detection limit of upcoming observatories (e.g., JWST, WFIRST), line-intensity mapping will fill the gap in understanding the role of low-luminosity systems in reionization.
- Line-intensity mapping will constrain the evolution of gas in galaxies, helping us describe the star-formation efficiencies in the early Universe.
- Continuum-intensity mapping provides a successful blueprint for measuring and interpreting/modeling statistical measurements.
- The experimental landscape is off to a running start!
  - ➡Its going to be a HARD measurement. But if CIB is a guide, progress will be fast!